WHIZARD NLO

Jürgen R. Reuter, DESY

1) Introduction to WHIZARD

↪ cf. Wolfgang Kilian's talk

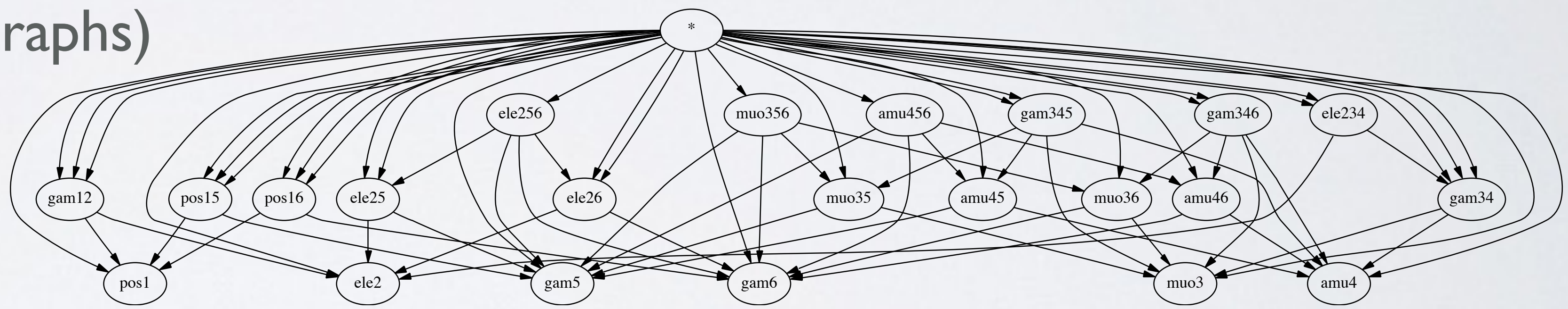
The WHIZARD Event Generator

WHIZARD v2.3.0 (27±2 July 2016) http://whizard.hepforge.org <whizard@desy.de>

WHIZARD Team: *Wolfgang Kilian, Thorsten Ohl, JRR, Simon Braß/Bijan Chokoufé/C. Fleper/Marco Sekulla/ Soyoung Shim/Christian Weiss/Florian Staub/Zhijie Zhao* + *1 Master*

EPJ C71 (2011) 1742

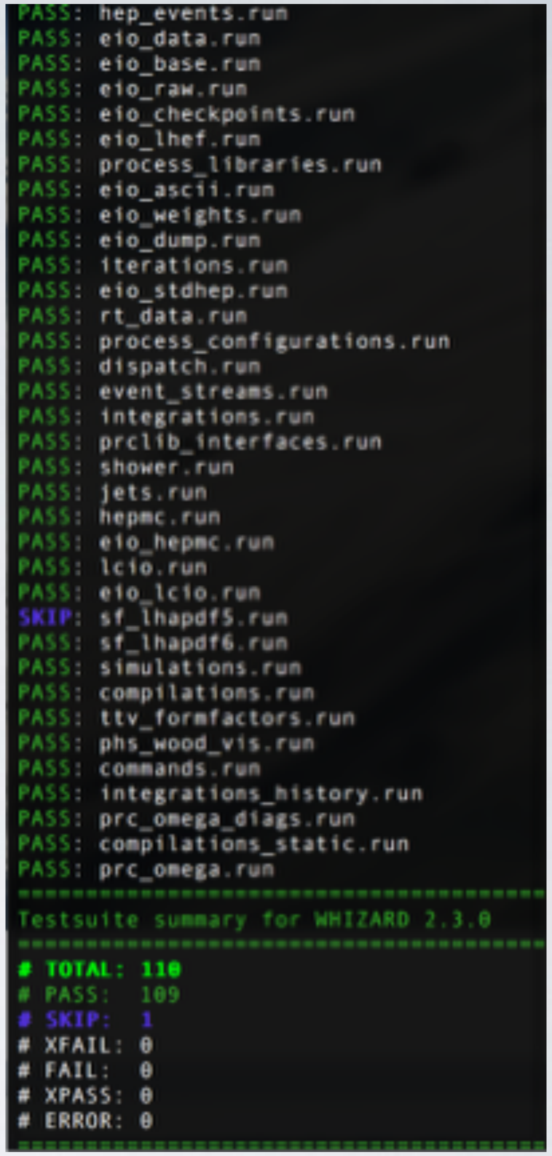
- Universal event generator for lepton and hadron colliders
- Modular package:
  - Phase space parameterization (resonances, collinear emission, Coulomb etc.)
  - O'Mega optimized matrix element generator (recursiveness via Directed Acyclical Graphs)

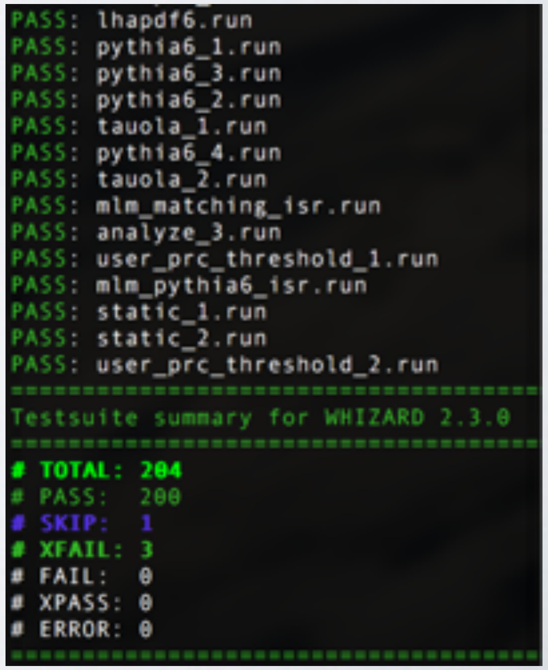


  - VAMP: adaptive multi-channel Monte Carlo integrator
  - CIRCE1/2: generator/simulation tool for lepton collider beam spectra
  - Lepton beam ISR — Kuraev/Fadin, 2003; Skrzypek/Jadach, 1991
  - Color flow formalism — Stelzer/Willenbrock, 2003; Kilian/Ohl/JRR/Speckner, 2011

WHIZARD: Installation and Run

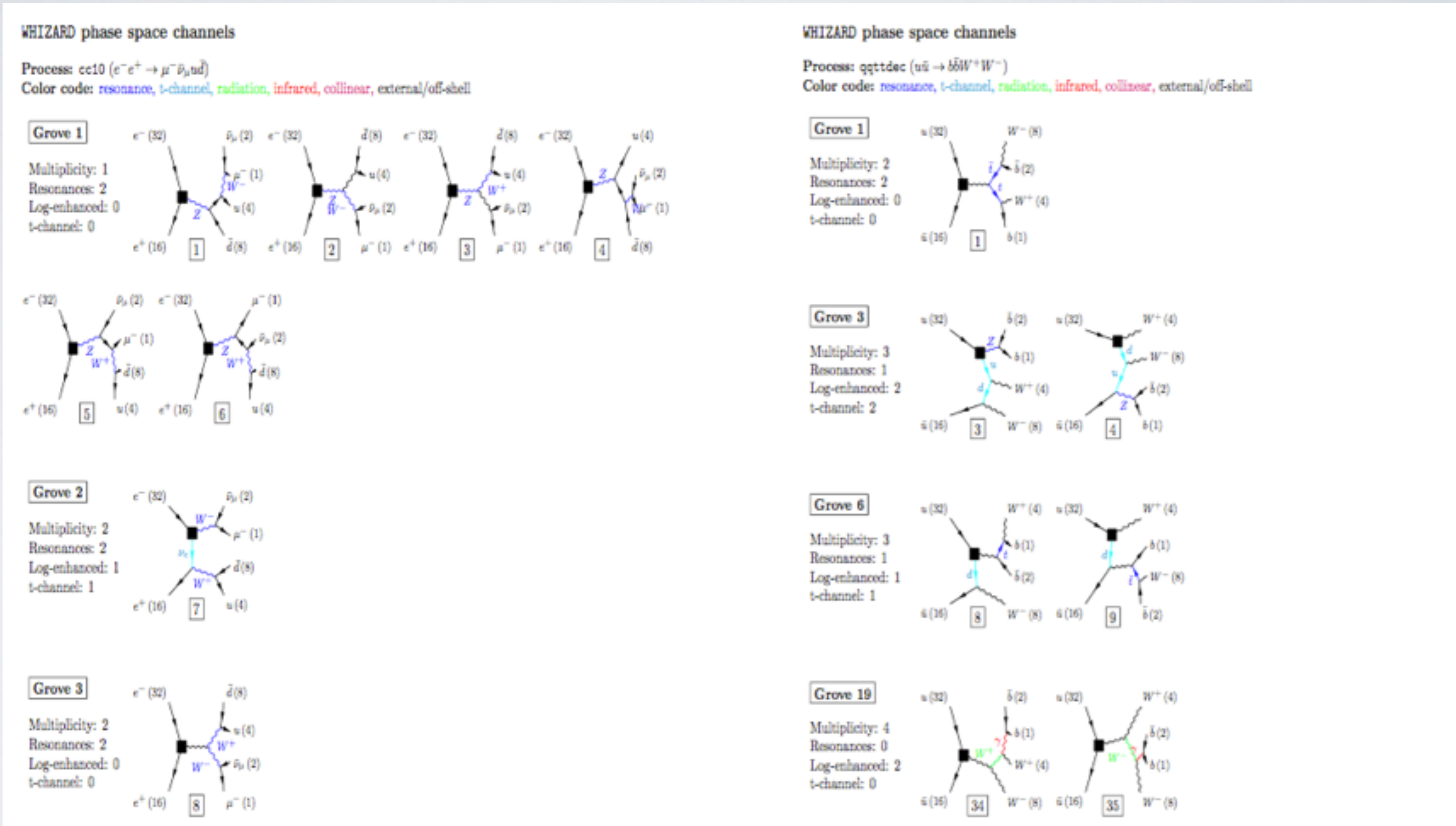
- Download: http://www.hepforge.org/archive/whizard/whizard-2.3.0.tar.gz
- Unpack it, intended to be installed in `/usr/local` (or locally)
- Create `build` directory and do `./configure`
- `make`, `[ make check ]`, `make install`
- Working directory: create `SINDARIN` steering file `<input>.sin`
- Working directory: run `whizard <input>.sin`
- Supported event formats: LHA, StdHep, LHEF (i-iii), HepMC, LCIO, div. ASCII
- Interfaces to external packages for Feynman rules, hadronization, event formats, analysis, jet clustering etc.: `FastJet`, `GoSam`, `GuineaPig(++)`, `HepMC`, `HOPPET`, `LCIO`, `LHAPDF(4/5/6)`, `LoopTools`, `OpenLoops`, `PYTHIA6`, `[PYTHIA8]`, `StdHep [internal]`





Phase Space Setup

WHIZARD algorithm: heuristics to classify phase-space topology, adaptive multi-channel mapping $\Longrightarrow$ `resonant, t-channel, radiation, infrared, collinear, off-shell`

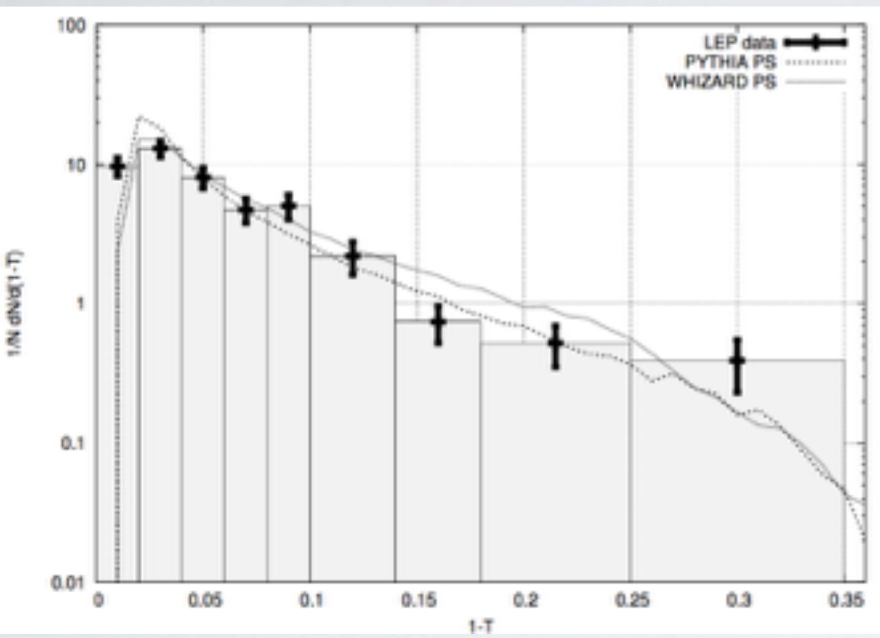


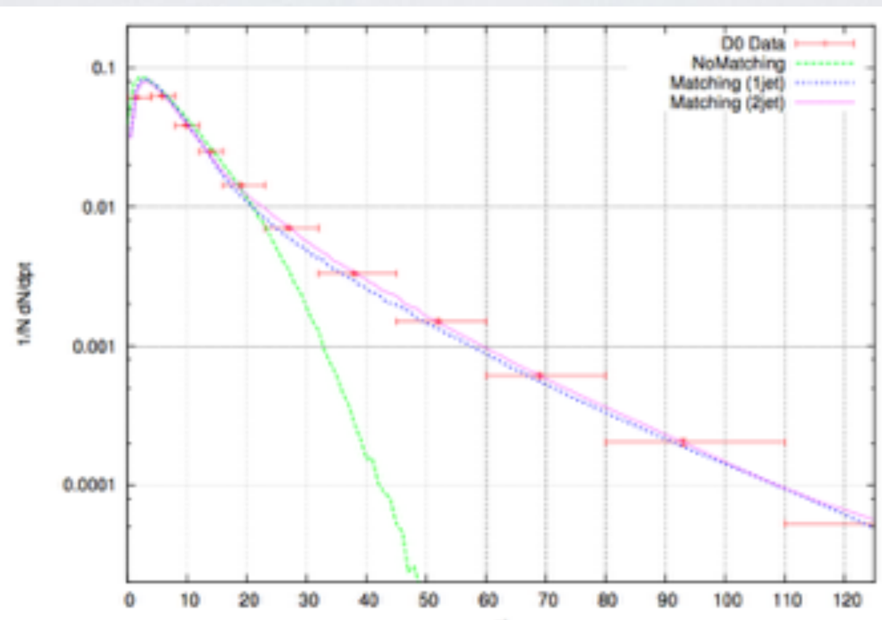
Complicated processes: factorization into production and decay with the `unstable` option

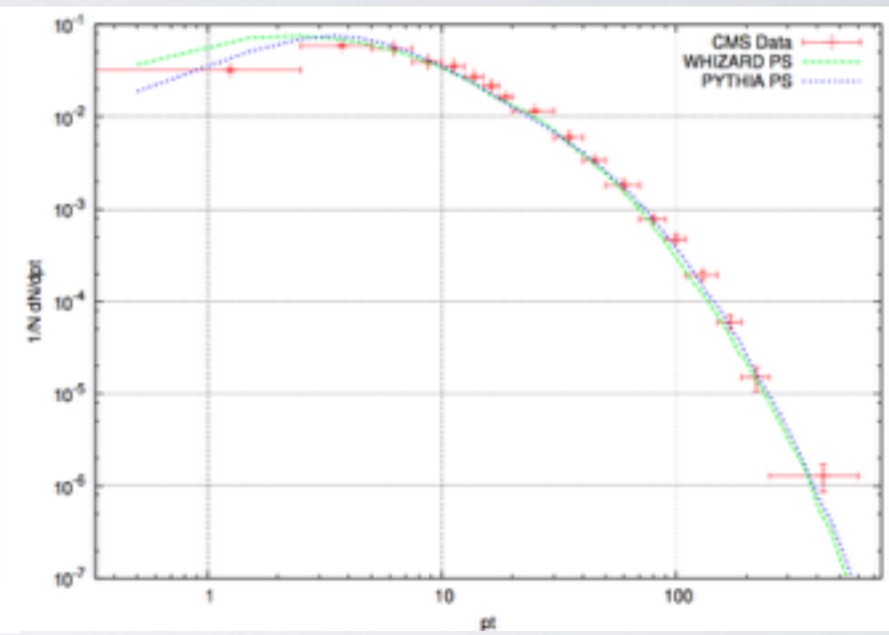
WHIZARD Parton Shower

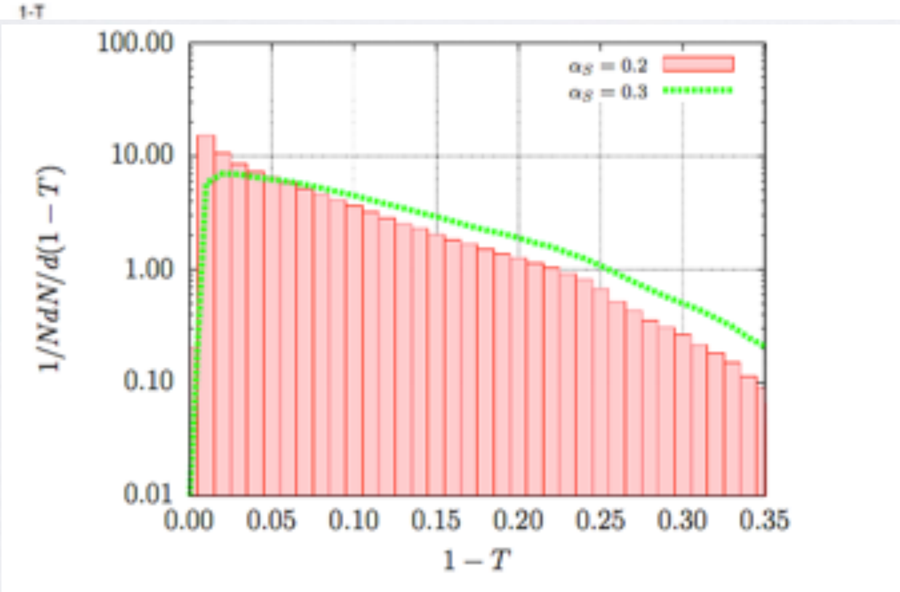
- Two independent implementations: kT-ordered QCD and Analytic QCD shower
- Analytic shower: no shower veto ⇒ exact shower history known, allows reweighting

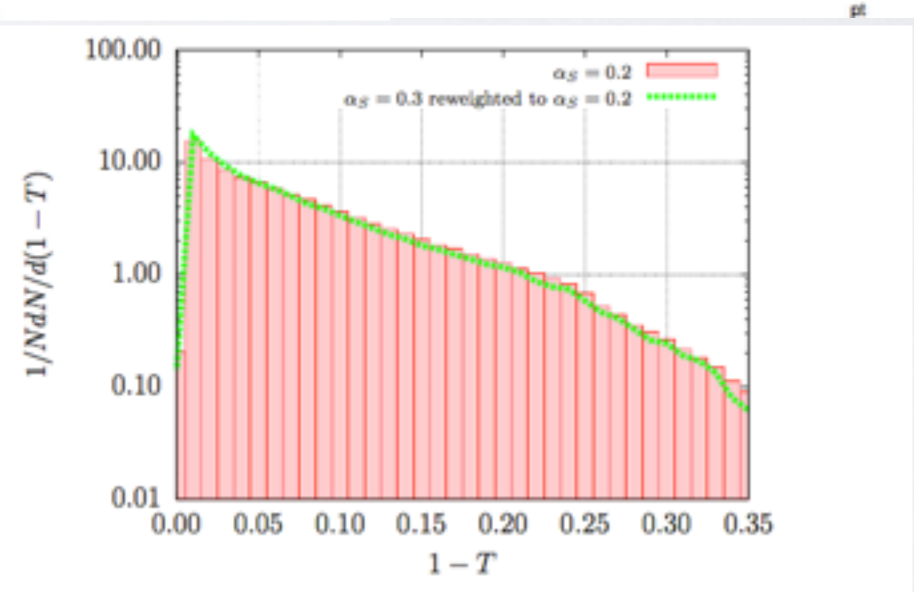
Kilian/JRR/Schmidt/Wiesler, JHEP **1204** 013 (2012)







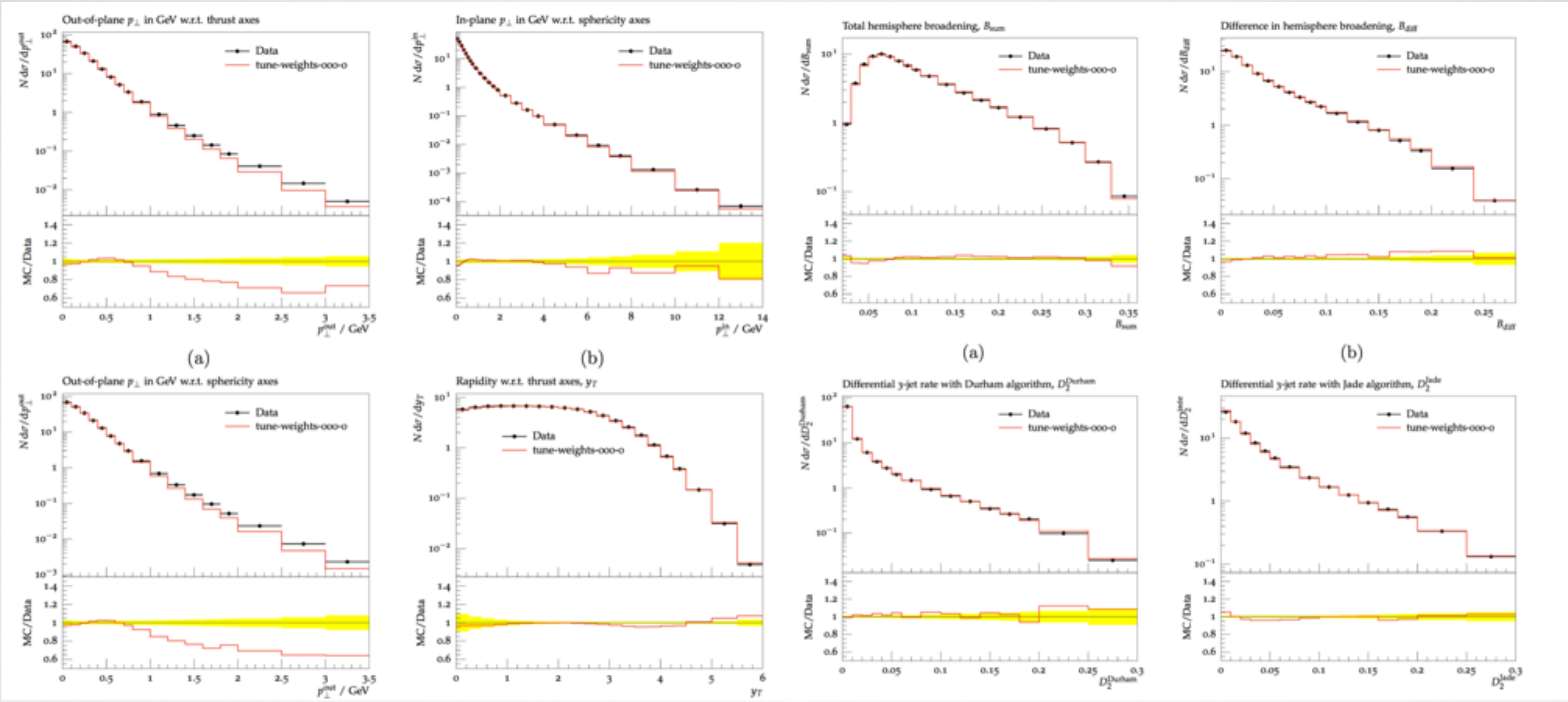




- Technical overhaul of the shower / merging part
- Plans: implement GKS matching, QED shower (also interleaved, infrastructure ready)

Tuning of the WHIZARD Parton Shower

- First tunes of both kT-ordered QCD and Analytic QCD shower Chokoufe/Englert/JRR, 2015
- Di- and Multijet data from LEP as given in `RIVET` analysis
- Usage of the `PROFESSOR` tool for determining the best fit Buckley et al., 2009



2) Automation of Fixed order NLO (QCD) in WHIZARD

NLO Development in WHIZARD

- Need for precision predictions that match (sub-) percent experimental accuracy
- mainly NLO corrections, but also QED and electroweak (ee)

Binoth Les Houches Interface (BLHA): Workflow

1. Process definition in SINDARIN (contract to One-Loop Program [OLP])
2. OLP generates code (Born/virtual interference), `WHIZARD` reads contract
3. NLO matrix element library loaded into `WHIZARD`

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Working NLO interfaces to:

(first focus on QCD corrections)

- ⋆ GoSam [G. Cullen et al.] ↪ Talk by Nicolas Greiner
- ⋆ OpenLoops [F. Cascioli et al.]

WHIZARD v2.3.0 contains beta version

QCD corrections (massless and massive emitters)

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alpha_power = 2
alphas_power = 0

process eett = e1,E1 => t, tbar
     { nlo_calculation = "full" }
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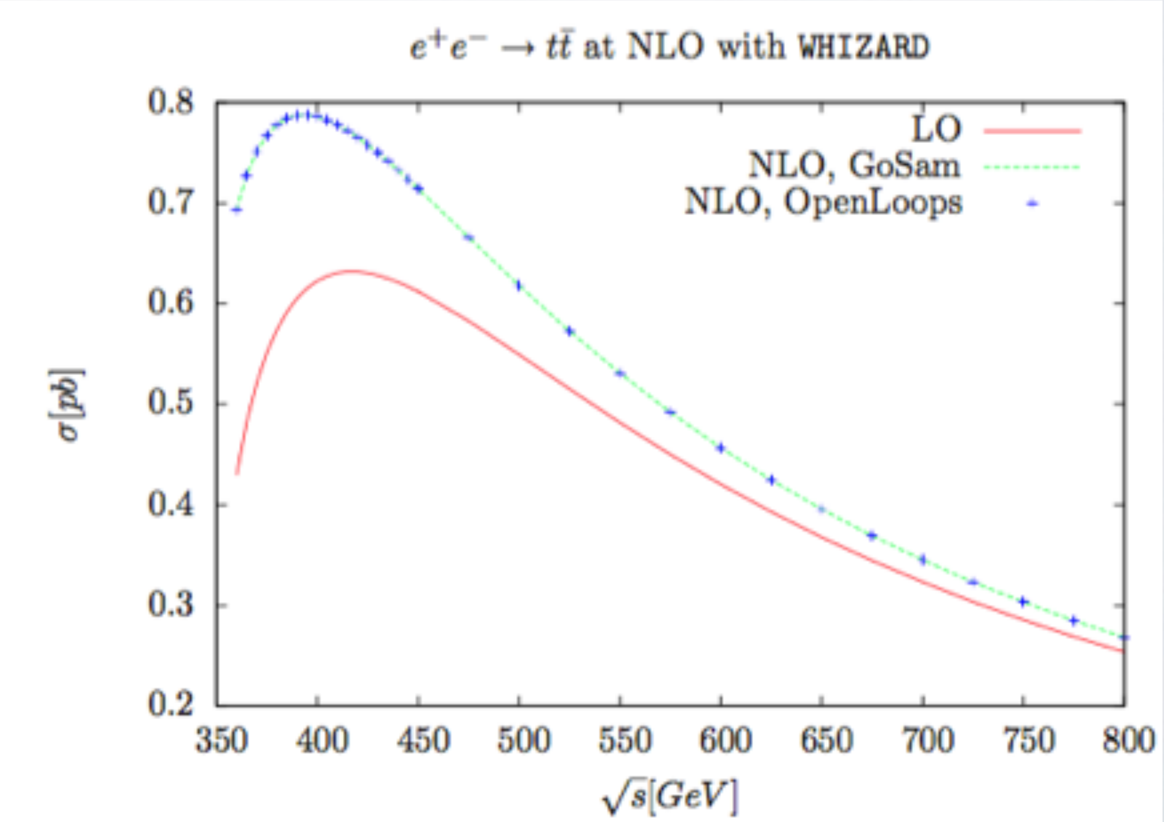

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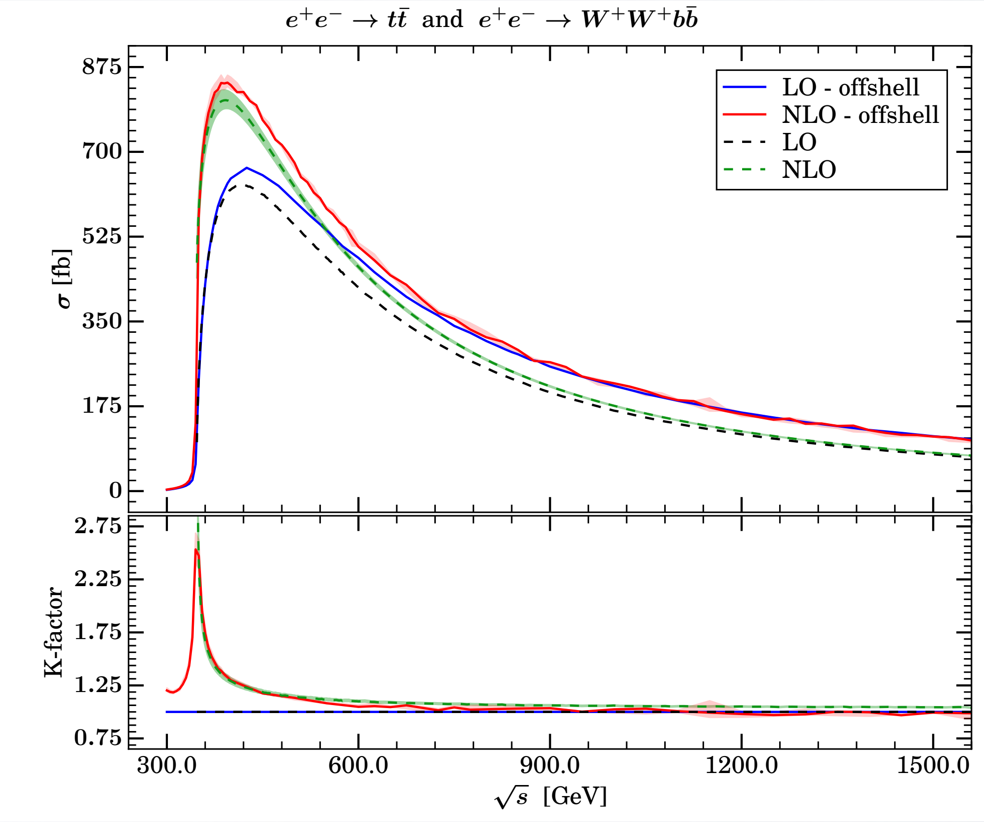

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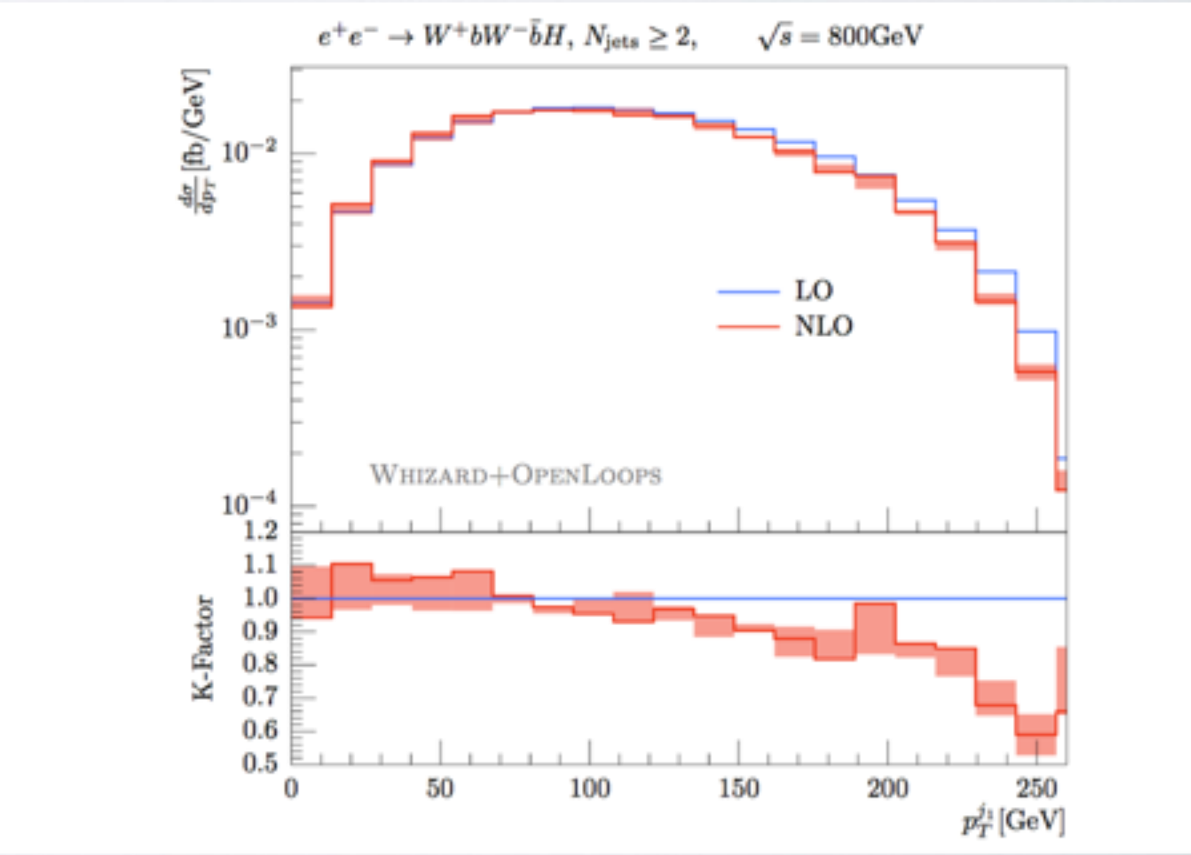

FKS Subtraction (Frixione/Kunszt/Signer)

Subtraction formalism to make real and virtual contributions separately finite

$$d\sigma^{\mathrm{NLO}} = \underbrace{\int_{n+1} \left(d\sigma^R - d\sigma^S\right)}_{\text{finite}} + \underbrace{\int_{n+1} d\sigma^S + \int_n d\sigma^V}_{\text{finite}}$$

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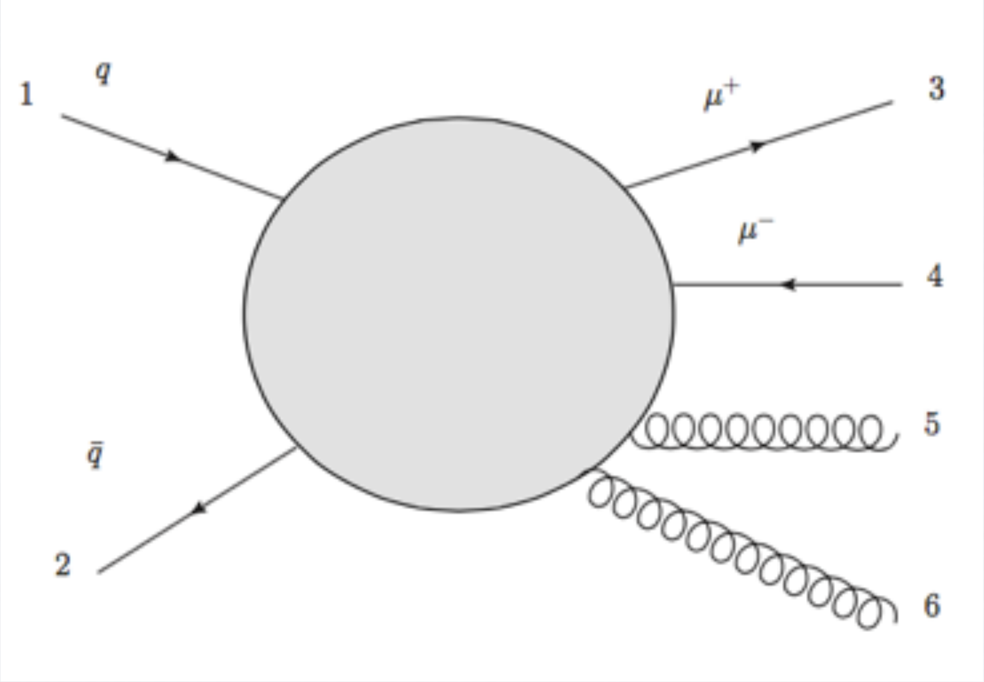

Automated subtraction terms in `WHIZARD`, algorithm:

- ✳ Find all singular pairs

$$\mathcal{I} = \{(1,5),(1,6),(2,5),(2,6),(5,6)\}$$

- ✳ Partition phase space according to singular regions

$$\mathbb{1} = \sum_{\alpha\in\mathcal{I}} S_\alpha(\Phi)$$

- ✳ Generate subtraction terms for singular regions

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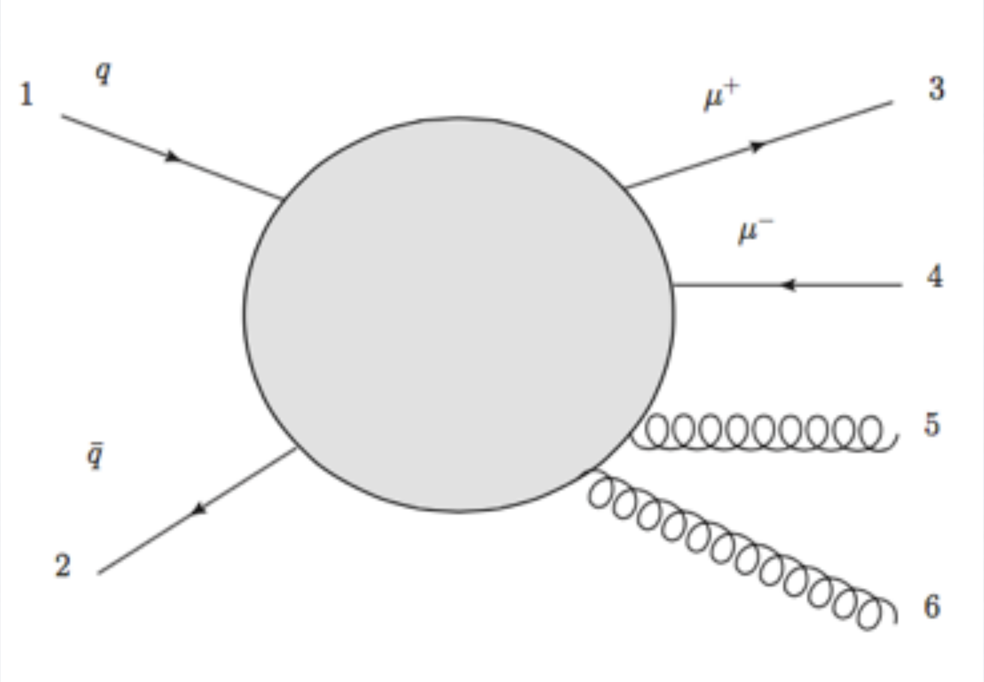

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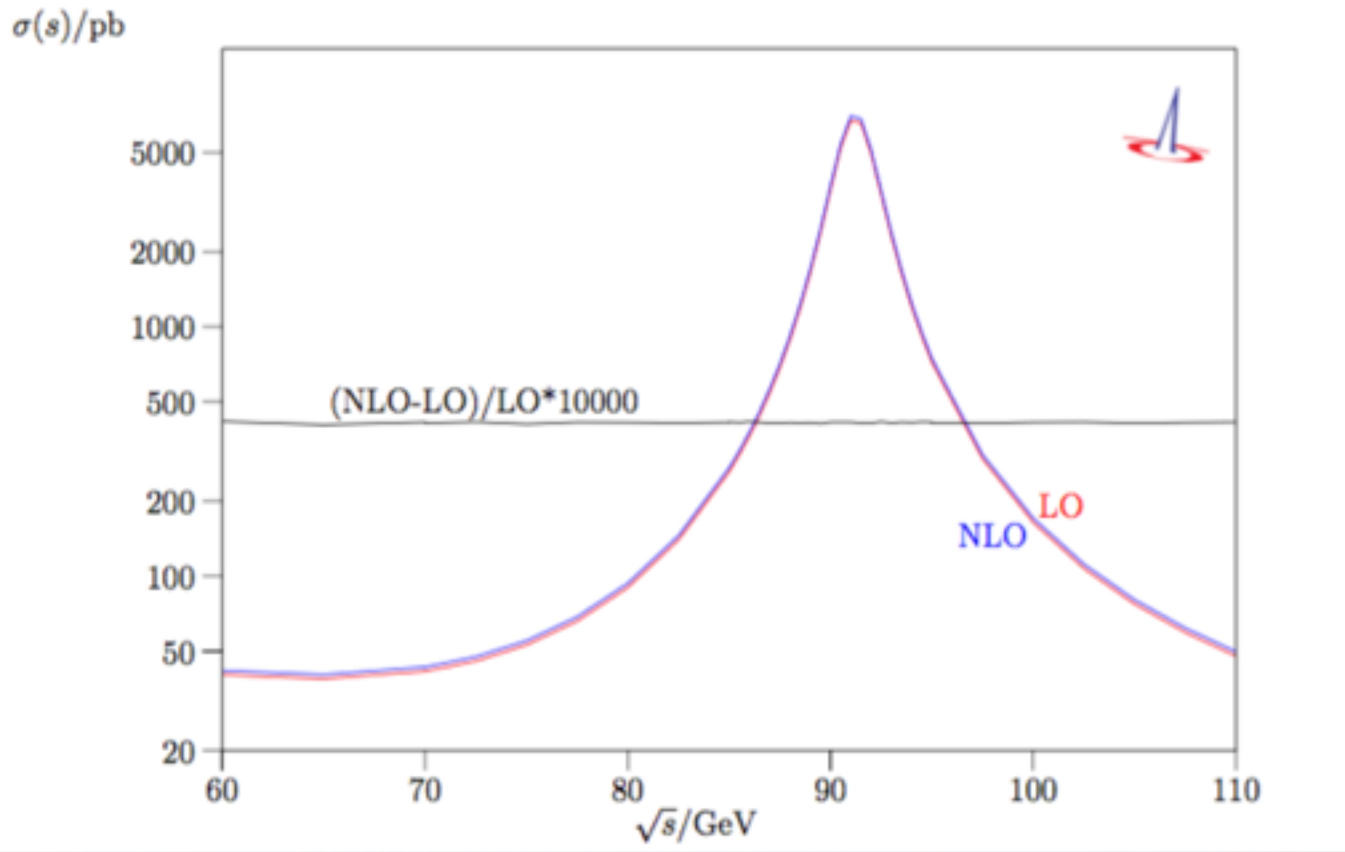
Soft subtraction involves color-correlated matrix elements:

$$\mathcal{B}_{kl} \sim -\sum_{\substack{\rm color\\ \rm spin}} \mathcal{A}^{(n)} \vec{\mathcal{Q}}(\mathcal{I}_k)\cdot\vec{\mathcal{Q}}(\mathcal{I}_l)\mathcal{A}^{(n)*},$$

Collinear subtraction involves spin-correlated matrix elements:

$$\mathcal{B}_{+-} \sim Re\left\{\frac{\langle k_{\rm em} k_{\rm rad}\rangle}{[k_{\rm em} k_{\rm rad}]} \sum_{\substack{\rm color\\ \rm spin}} \mathcal{A}_+^{(n)} \mathcal{A}_-^{(n)*}\right\}$$

Examples and Validation



Simplest benchmark process:

$$e^+e^- \to q\bar{q} \quad \text{with} \quad \left(\sigma^{\rm NLO} - \sigma^{\rm LO}\right)/\sigma^{\rm LO} = \alpha_s/\pi$$

Plot for total cross section for fixed strong coupling constant

Excerpt of validated QCD NLO processes

- $e^+e^- \to q\bar{q}$
- $e^+e^- \to q\bar{q}g$
- $e^+e^- \to \ell^+\ell^- q\bar{q}$
- $e^+e^- \to \ell^+\nu_\ell q\bar{q}$
- $e^+e^- \to t\bar{t}$
- $e^+e^- \to tW^-b$
- $e^+e^- \to W^+W^-b\bar{b}$
- $e^+e^- \to t\bar{t}H$

- Cross-checks with `MG5_aMC@NLO, Sherpa, MUNICH`
- Phase space integration performs great (*V*, *R*, *S*)
- Plan to also support `NJet` [Badger et al.]

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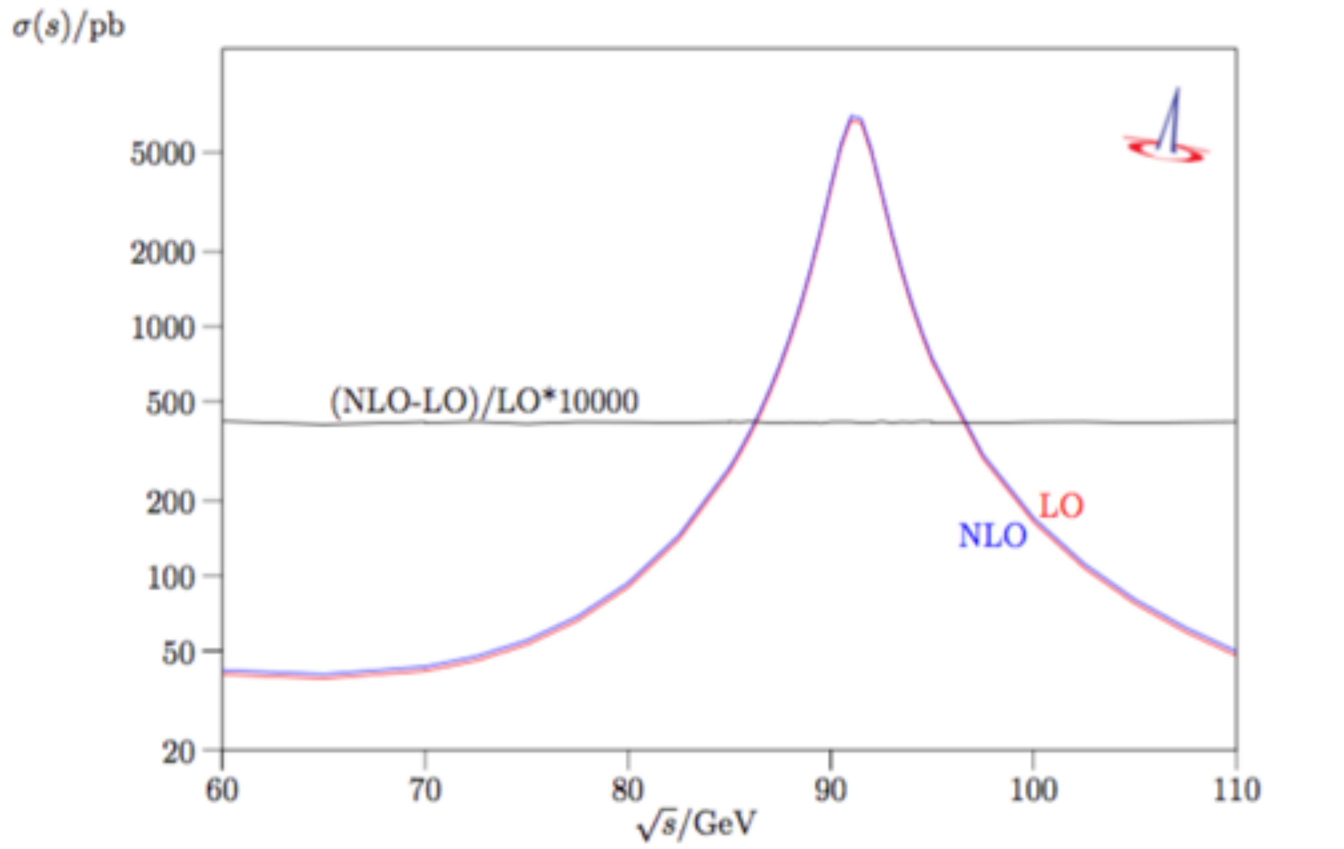

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✦ QCD NLO infrastructure in pp complete

✦ First attempts on electroweak corrections, interfacing the `RECOLA` code [Denner et al.]

Resonance mappings for NLO processes

- Amplitudes (except for pure QCD/QED) contain resonances (*Z, W, H, t*)
- In general: resonance masses *not* respected by modified kinematics of subtraction terms
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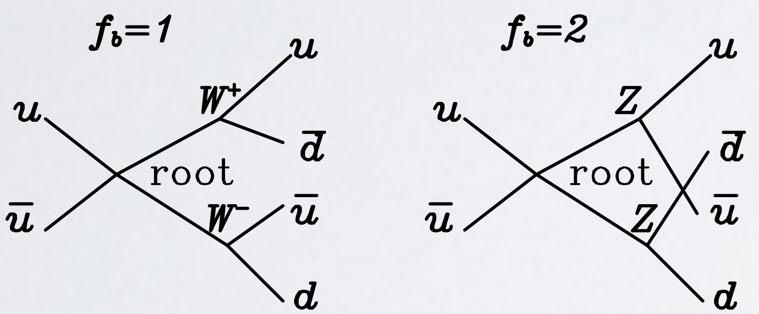

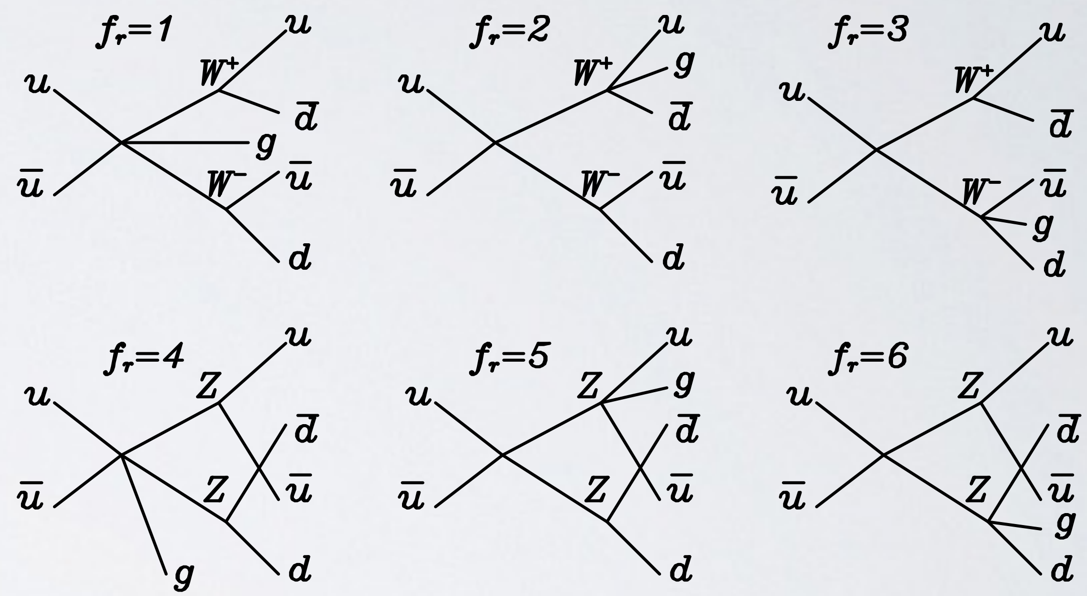

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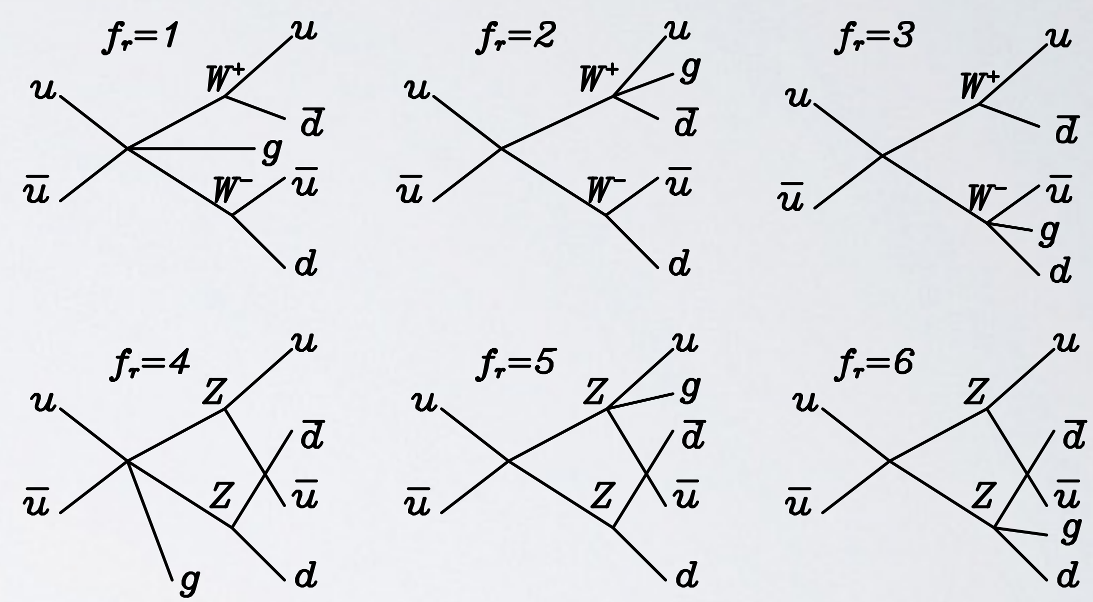

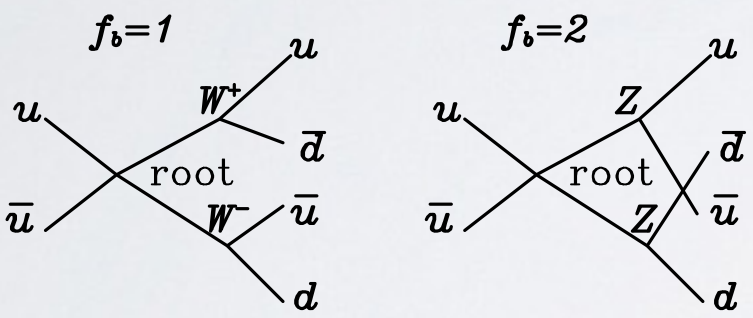

- WHIZARD complete automatic implementation: example $e^+ e^- \to \mu\mu bb$ (*ZZ, ZH* histories)

It	Calls	Integral[fb]	Error[fb]	Err[%]	Acc	Eff[%]	Chi2	N[It]
1	11988	9.6811847E+00	6.42E+00	66.30	72.60*	0.65		
2	11959	2.8539703E+00	2.35E-01	8.25	9.02*	0.69		
3	11936	2.4907574E+00	6.54E-01	26.25	28.68	0.35		
4	11908	2.7695559E+00	9.67E-01	34.91	38.09	0.30		
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standard FKS

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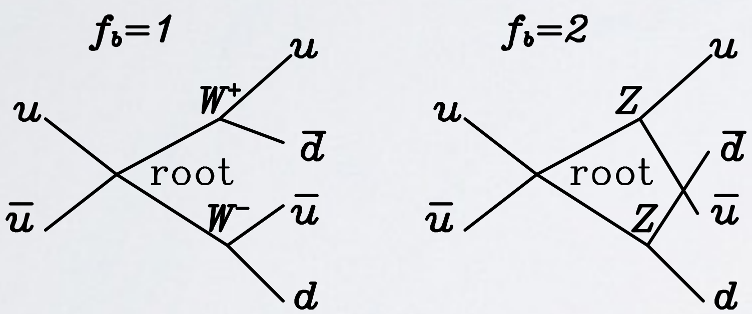

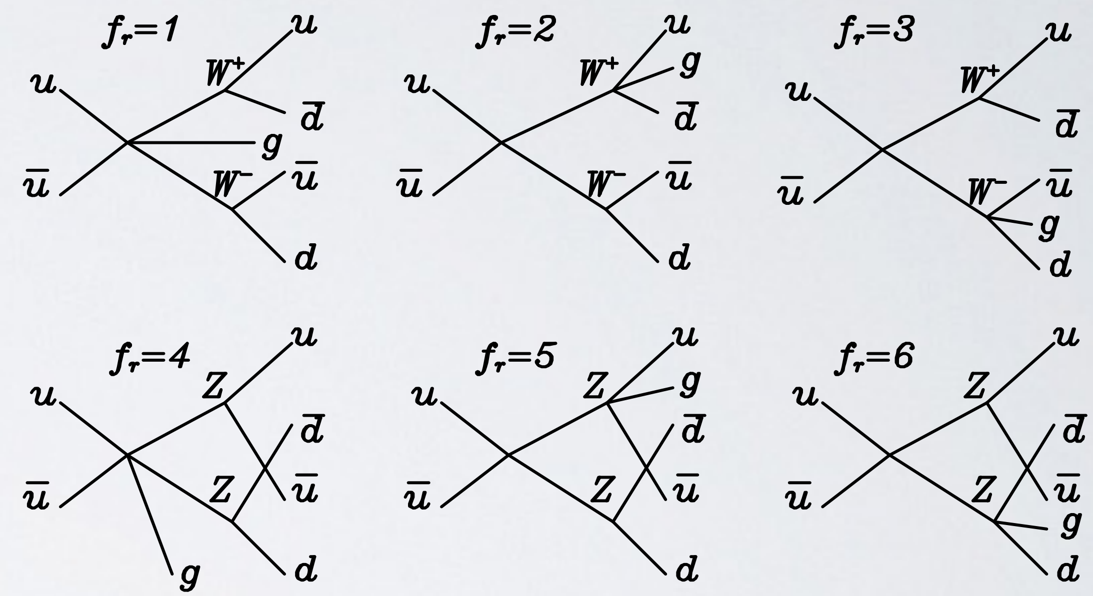

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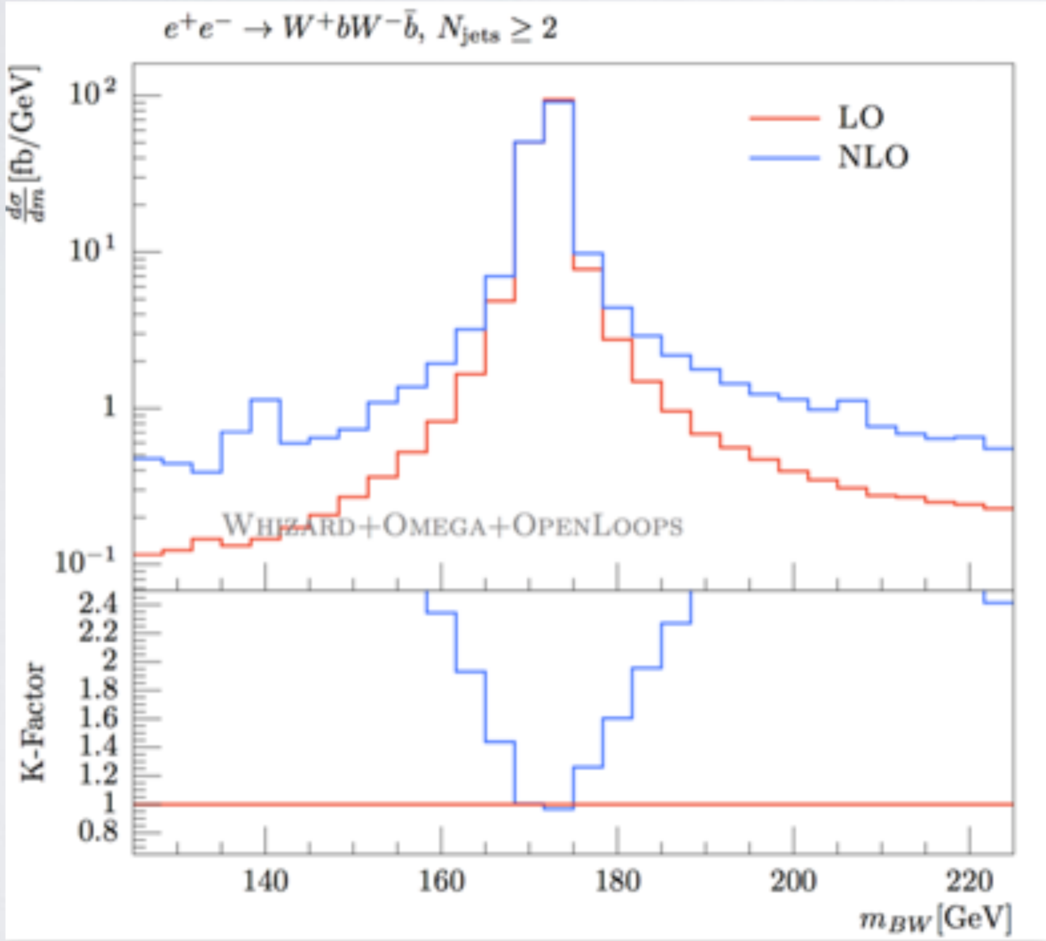
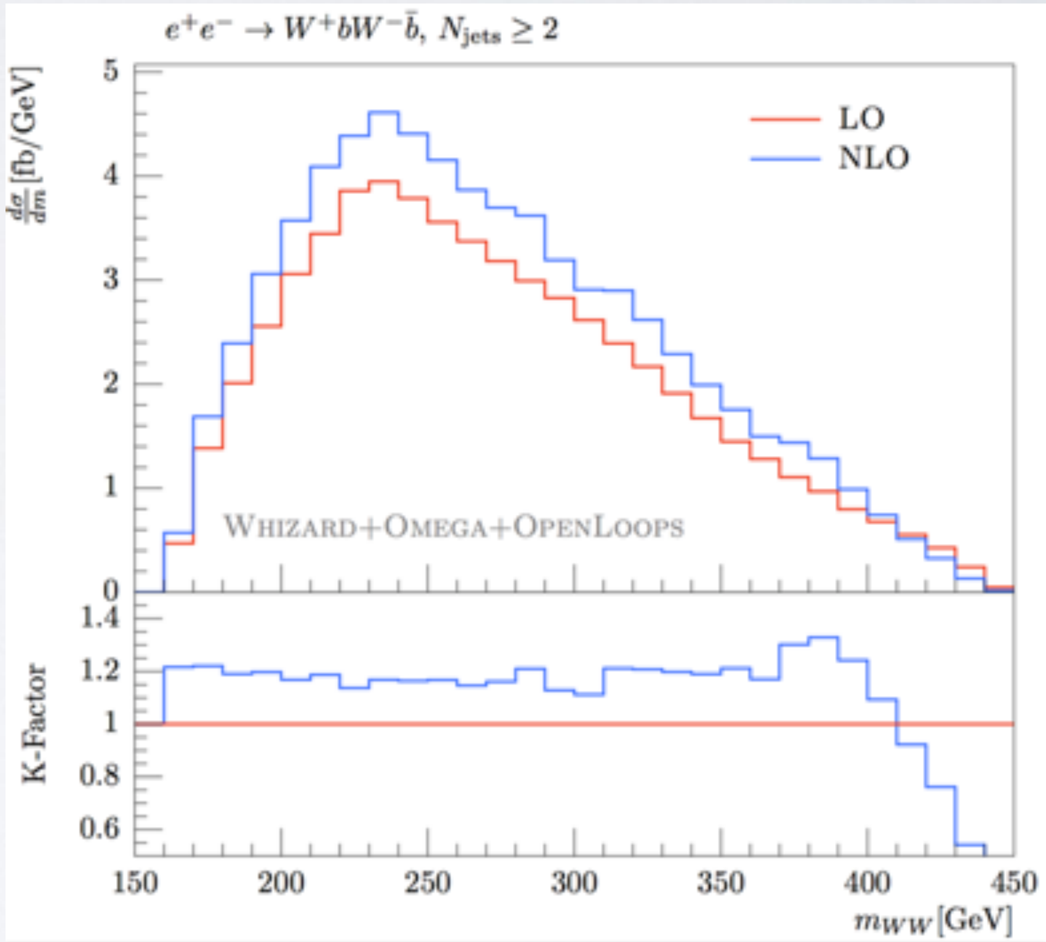
3	11936	2.9277880E+00	4.09E-02	1.40	1.52*	14.48		
4	11902	2.8512337E+00	3.98E-02	1.40	1.52*	13.70		
5	11874	2.8855399E+00	3.87E-02	1.34	1.46*	17.15		
5	59662	2.8842006E+00	2.04E-02	0.71	1.72	17.15	0.53	5

FKS with resonance mappings

NLO Fixed-Order Events

- Add weights of real emission events to weight of Born kinematics using the FKS mapping
- Output weighted events in `WHIZARD` (e.g. using `HepMC`), then analysis with `Rivet`
- Example process: $e^+e^- \to W^+W^-b\bar{b}$





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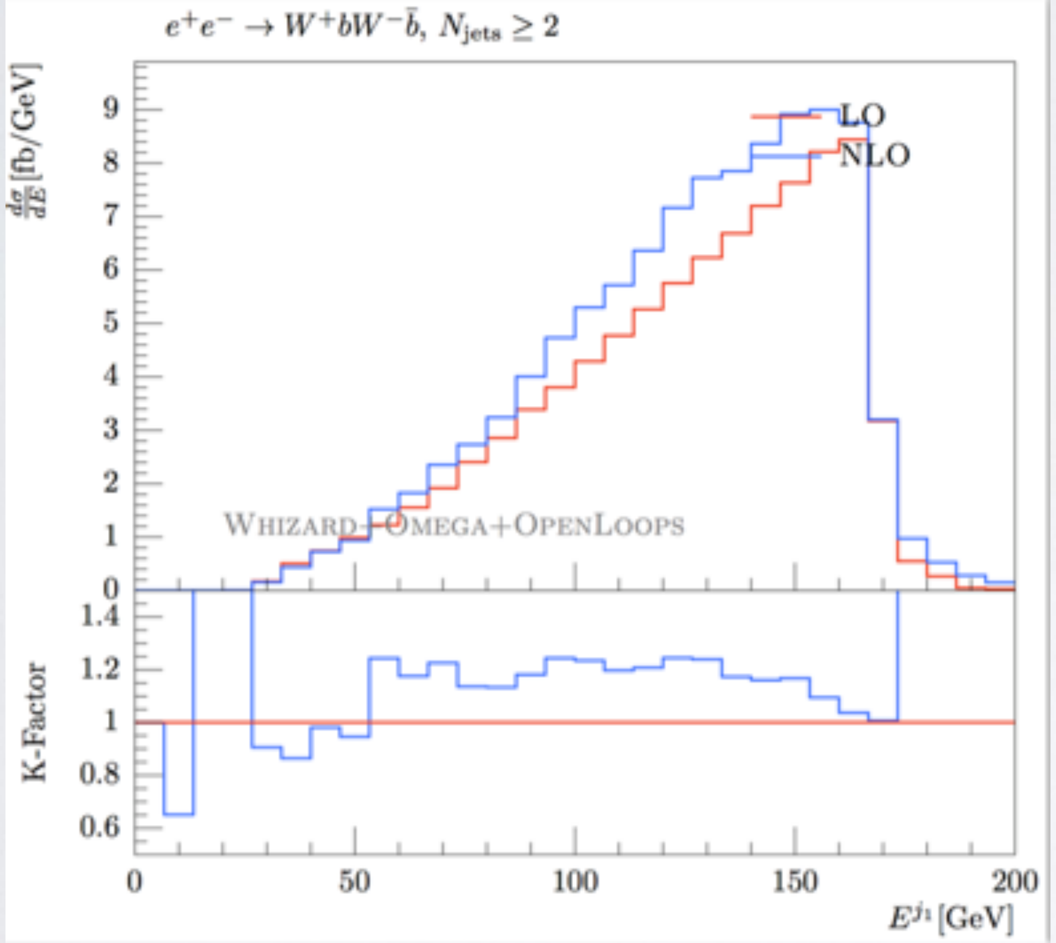
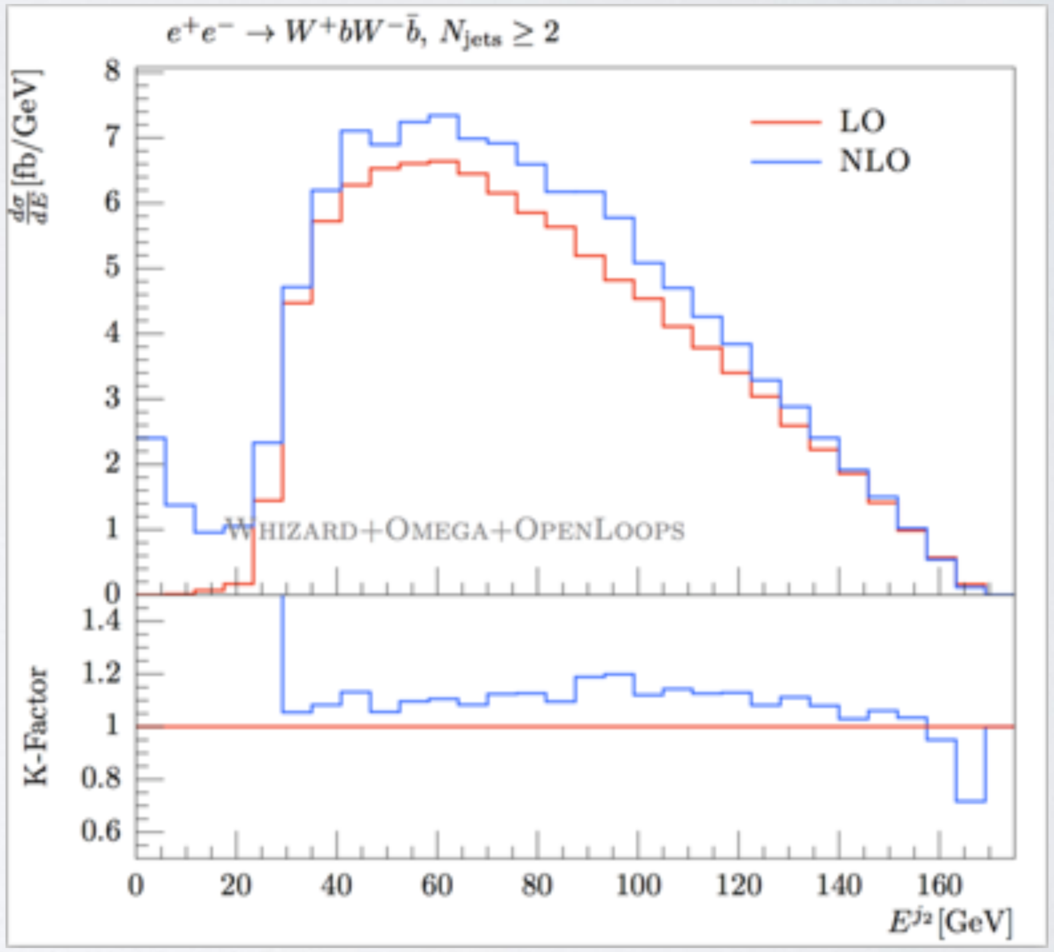
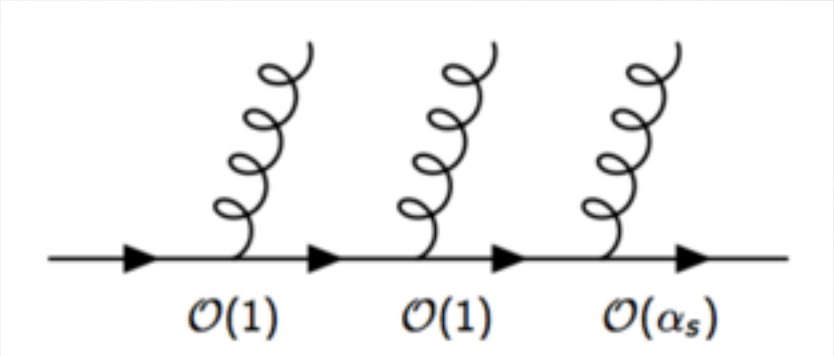




Automated POWHEG Matching in WHIZARD

- Soft gluon emissions before hard emission generate large logs
- Perturbative α_s : $|\mathcal{M}_{\rm soft}|^2 \sim \frac{1}{k_T^2} \to \log \frac{k_T^{\rm max}}{k_T^{\rm min}}$
- Consistent matching of NLO matrix element with shower
- POWHEG method: hardest emission first [Nason et al.]



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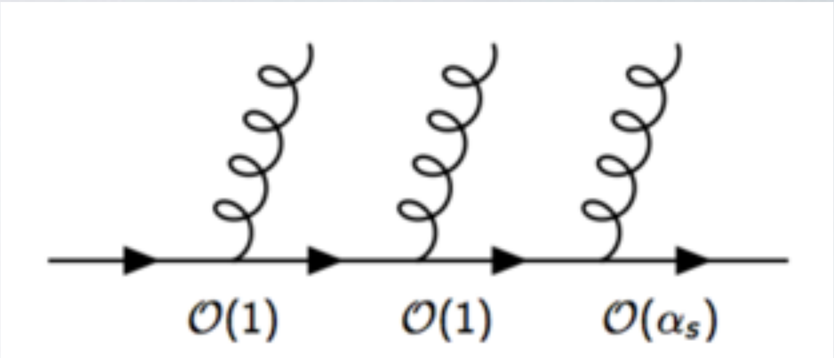


- Complete NLO events

$$\overline{B}(\Phi_n) = B(\Phi_n) + V(\Phi_n) + \int d\Phi_{\rm rad} R(\Phi_{n+1})$$

- POWHEG generate events according to the formula:

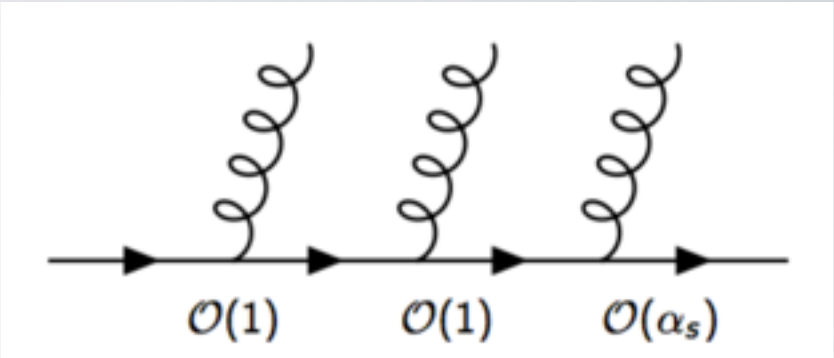
$$d\sigma = \overline{B}(\Phi_n) \left[\Delta_R^{\rm NLO}(k_T^{\rm min}) + \Delta_R^{\rm NLO}(k_T) \frac{R(\Phi_{n+1})}{B(\Phi_n)} d\Phi_{\rm rad} \right]$$

- Uses the modified Sudakov form factor:

$$\Delta_R^{\rm NLO}(k_T) = \exp \left[- \int d\Phi_{\rm rad} \frac{R(\Phi_{n+1})}{B(\Phi_n)} \theta(k_T(\Phi_{n+1}) - k_T) \right]$$

Automated POWHEG Matching in WHIZARD

- Soft gluon emissions before hard emission generate large logs
- Perturbative α_s : $|\mathcal{M}_{\rm soft}|^2 \sim \frac{1}{k_T^2} \to \log \frac{k_T^{\rm max}}{k_T^{\rm min}}$
- Consistent matching of NLO matrix element with shower
- POWHEG method: hardest emission first [Nason et al.]



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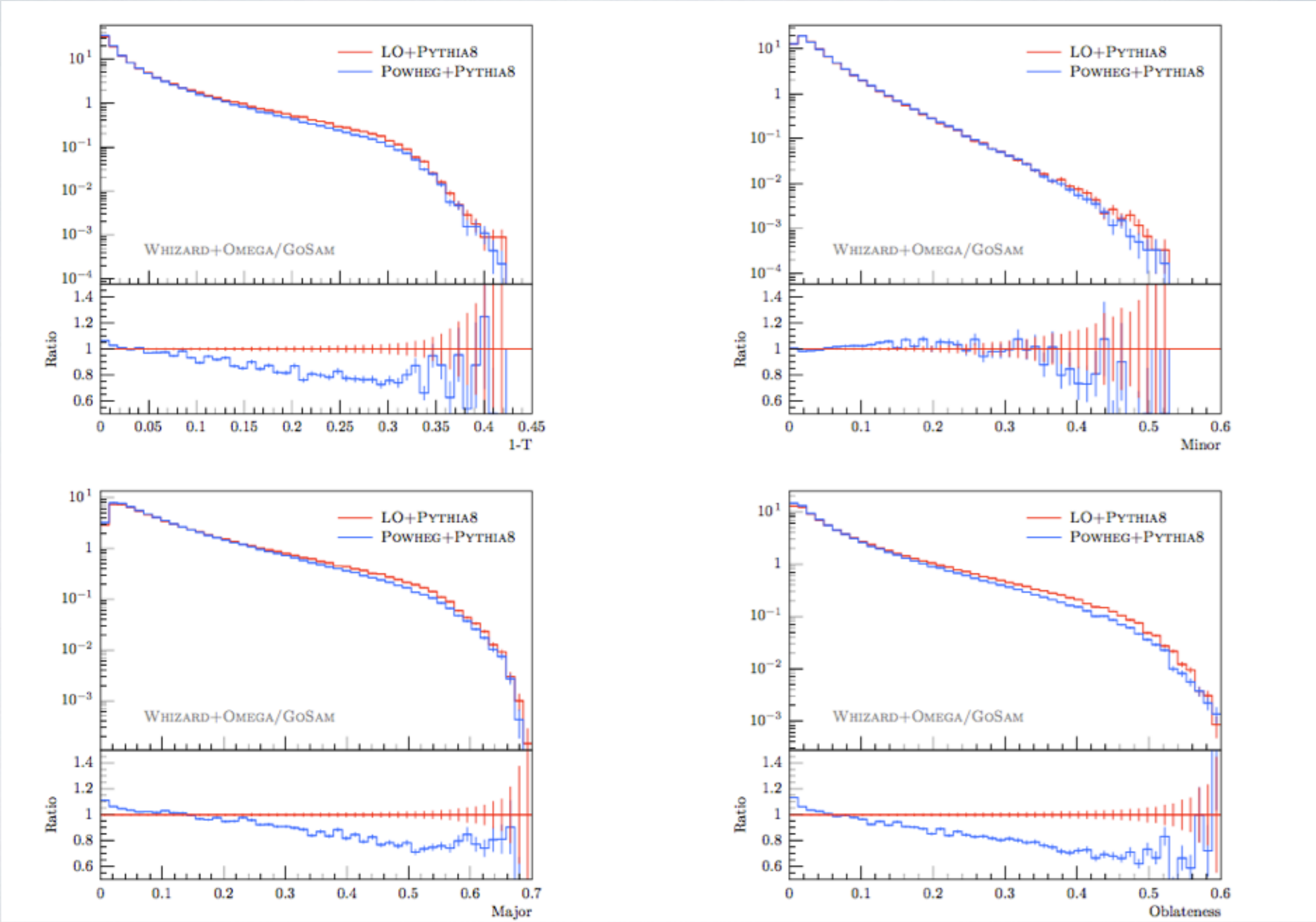
- Hardest emission: $k_T^{\rm max}$; shower with imposing a veto
- $\overline{B} < 0$ if virtual and real terms larger than Born: shouldn't happen in perturbative regions
- Reweighting such that $\overline{B} > 0$ for all events
- POWHEG: Positive Weight Hardest Emission Generator own implementation in `WHIZARD`

POWHEG Matching, example: e+e- to dijets



Prime WHIZARD LHC example: Drell-Yan

- Simplest hadron collider processes: $pp \to (Z \to ll) + X$, $pp \to (W \to l\nu) + X$, $pp \to ZZ + X$
- Standard candle processes

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- Simplest hadron collider processes: *pp → (Z → ll) + X, pp → (W → lν) + X, pp → ZZ + X*
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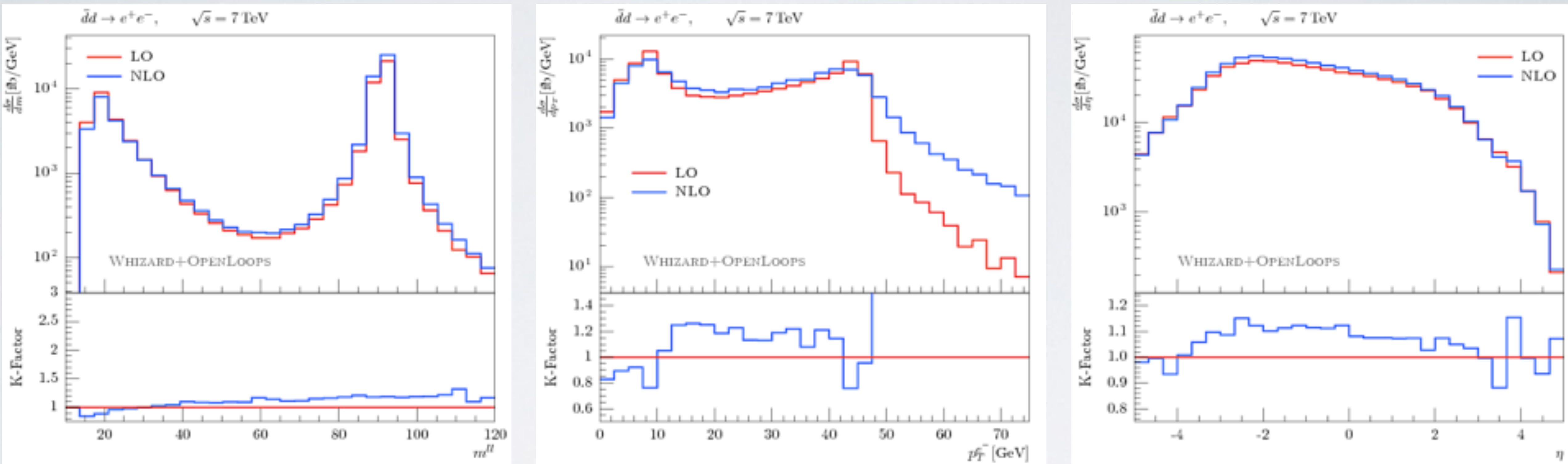

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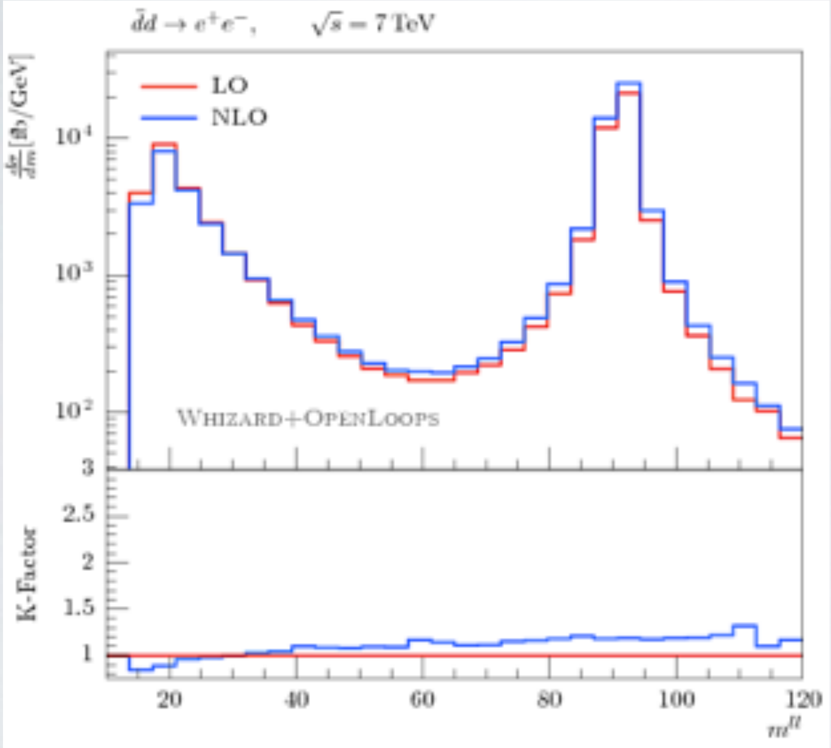

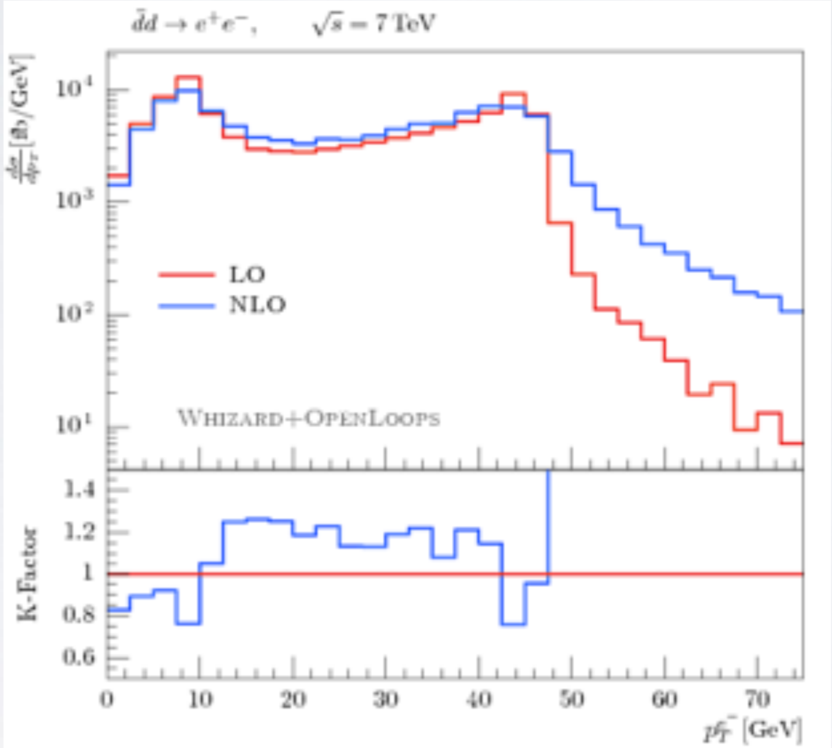

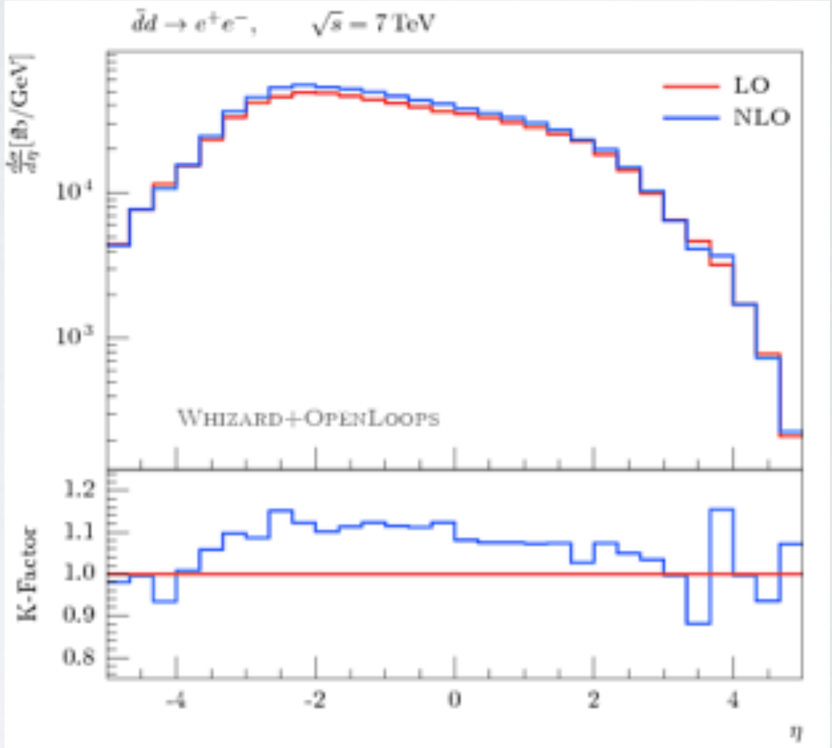

Open points / next steps:

- Flavor sums in fixed-order event generation
- Color in initial and final state (already validated for top decay)
- Gluons in the initial state
- Next processes: $pp \to Zj + X$, $pp \to tt + X$, $pp \to jj + X$
- automated POWHEG matching for hadron collider

Lepton colliders: *tt* and *ttH* (on- & off-shell)

- Paradigm processes at lepton colliders: precision determination of m_t and Y_t
- Major background for EW measurements (*VVV* and VBS); any [most] BSM searches
- Investigate processes of increasing complexity: $2 \to 2$ to $2 \to 4$ to $2 \to 6$

$e^+e^- \to$	$n_{\text{loop diags}}$	Max. prop.	n_{hel}
$t\bar{t}$	2	3	16
$W^+W^-b\bar{b}$	157	5	144
$b\bar{b}\bar{\nu}_e e^-\nu_\mu\mu^+$	830	5	16
$t\bar{t}H$	17	4	16
$bW^+\bar{b}W^-H$	1548	6	144
$b\bar{b}\bar{\nu}_e e^-\nu_\mu\mu^+H$	7436	6	16

On-Shell process: $e^+e^- \to t\bar{t}$

- NLO QCD [Jersak/Laermann/Zerwas, 1982]
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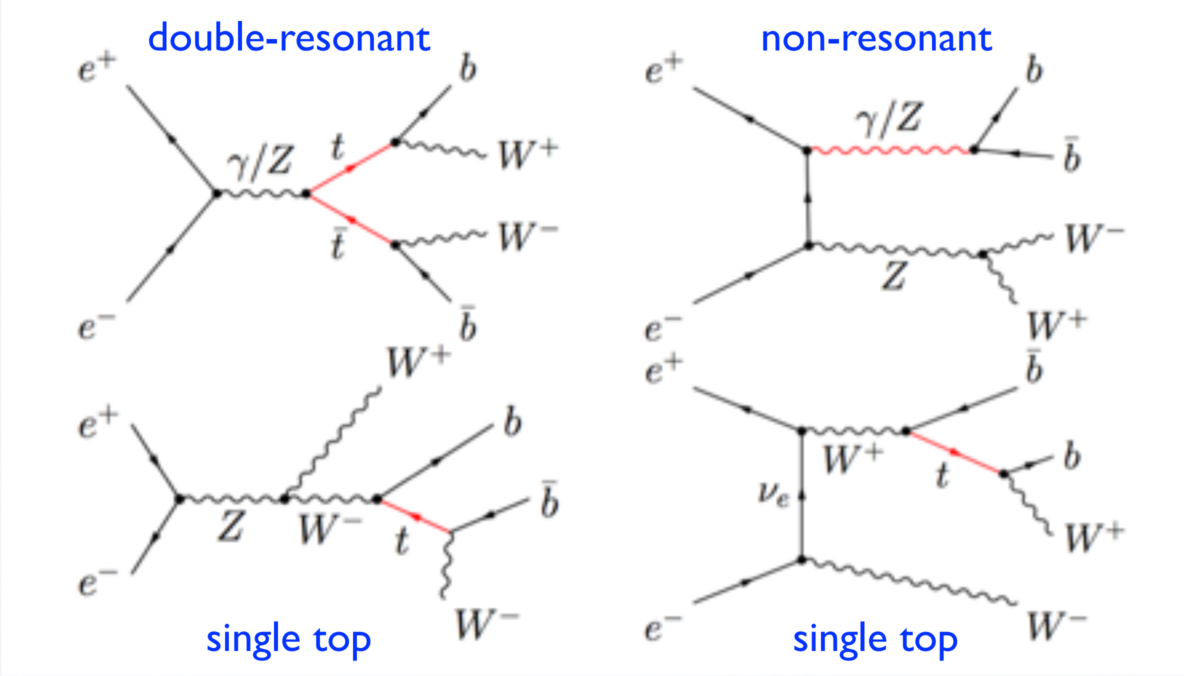

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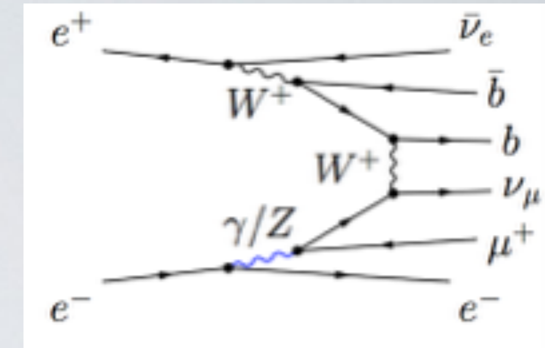

- Cross checks for 2 → 2 and 2 → 4 processes with `Sherpa` and `Munich`
- Using massive *b* quarks: no cuts necessary for $e^+e^- \to W^+W^-bb$
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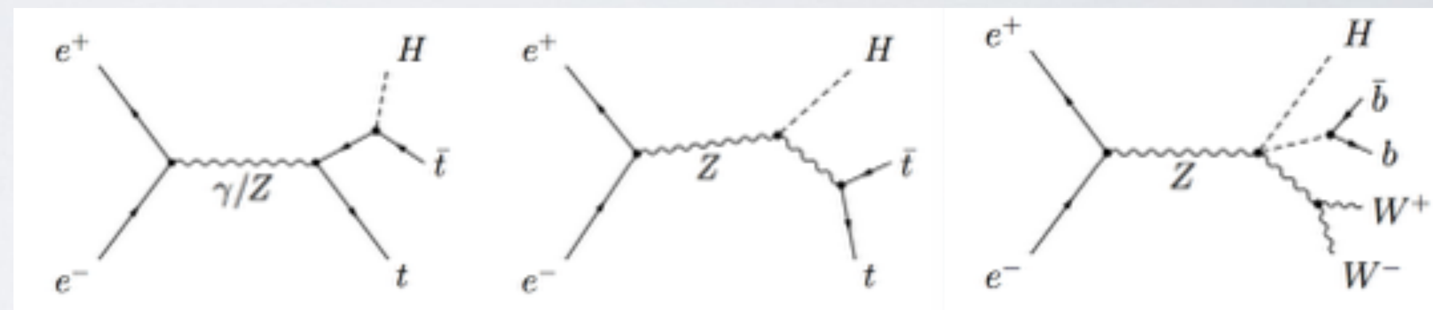
- *ttH* production: 8% contamination from Higgsstrahlung
- Contribution from quartic SM vertices



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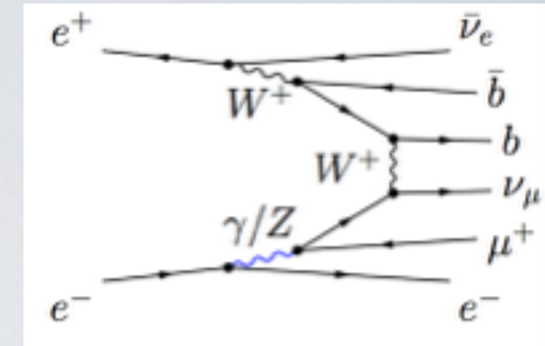

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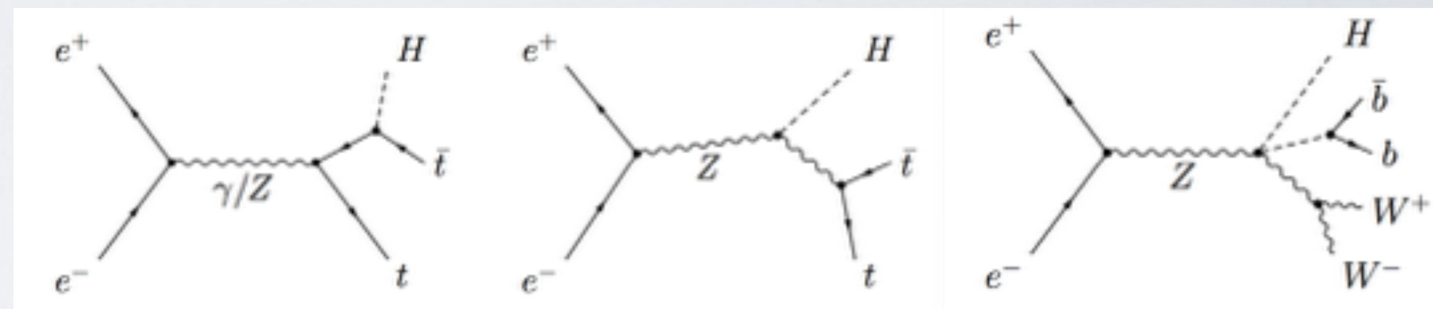

INPUT PARAMETERS:

$$m_Z = 91.1876\,\text{GeV}, \qquad m_W = 80.385\,\text{GeV}$$
$$m_b = 4.2\,\text{GeV}, \qquad m_t = 173.2\,\text{GeV}.$$

$$\Gamma^{\text{LO}}_{t\to Wb} = 1.4986\,\text{GeV}, \qquad \Gamma^{\text{NLO}}_{t\to Wb} = 1.3681\,\text{GeV},$$
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$$m_H = 125\ \text{GeV} \qquad \Gamma_H = 0.000431\ \text{GeV}$$

$$\Gamma^{\text{LO}}_Z = 2.4409\,\text{GeV}, \qquad \Gamma^{\text{NLO}}_Z = 2.5060\,\text{GeV},$$
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complex mass scheme:

$$\mu_i^2 = M_i^2 - \mathrm{i}\Gamma_i M_i \qquad \text{for } i = \mathrm{W, Z, t, H}$$

$$s_w^2 = 1 - c_w^2 = 1 - \frac{\mu_\mathrm{W}^2}{\mu_\mathrm{Z}^2}$$

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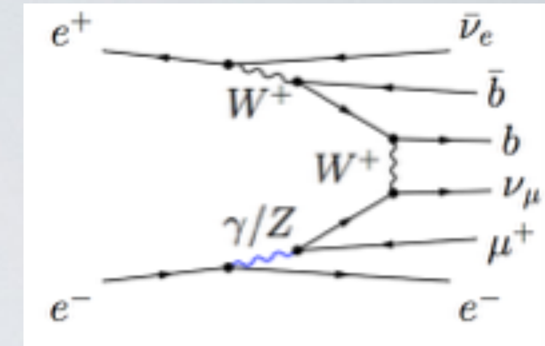

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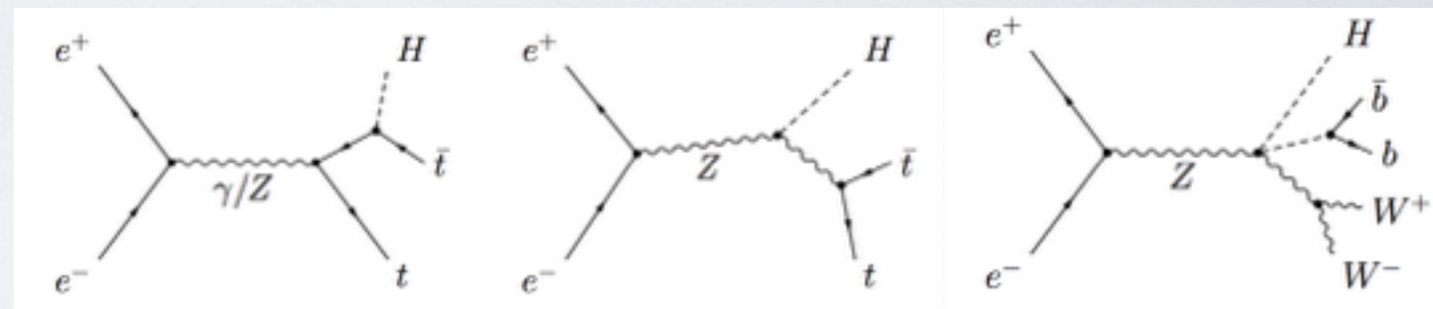

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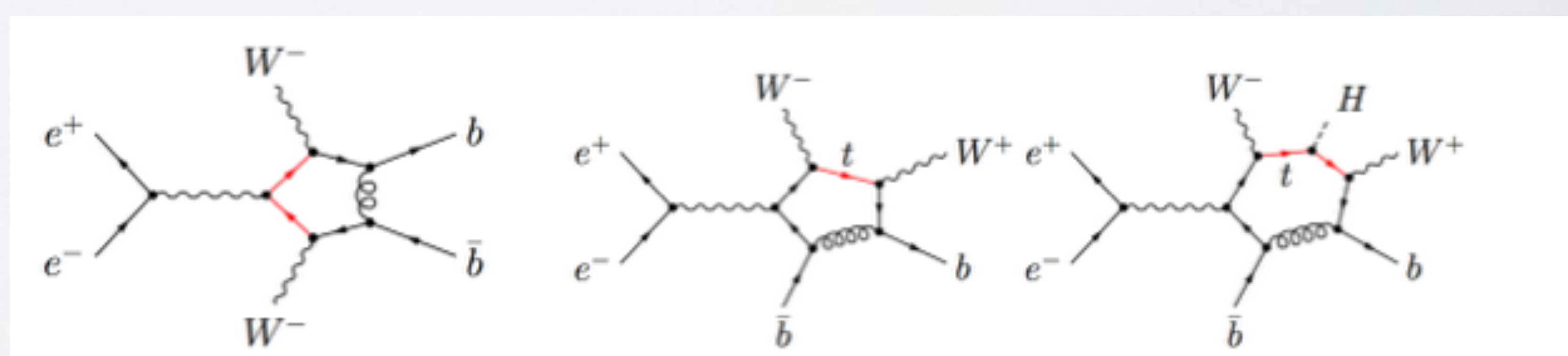
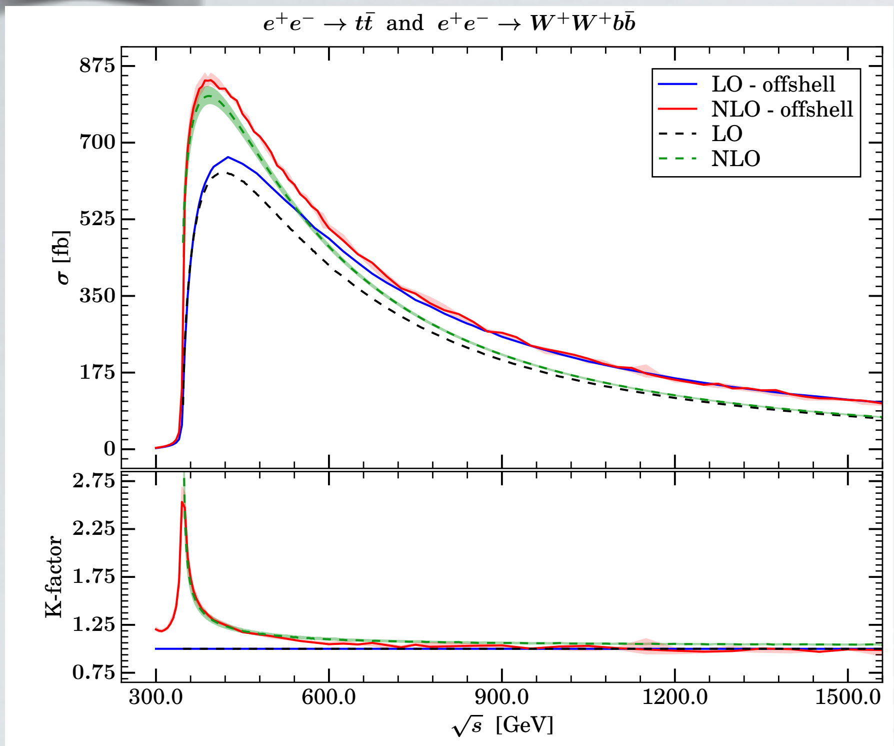
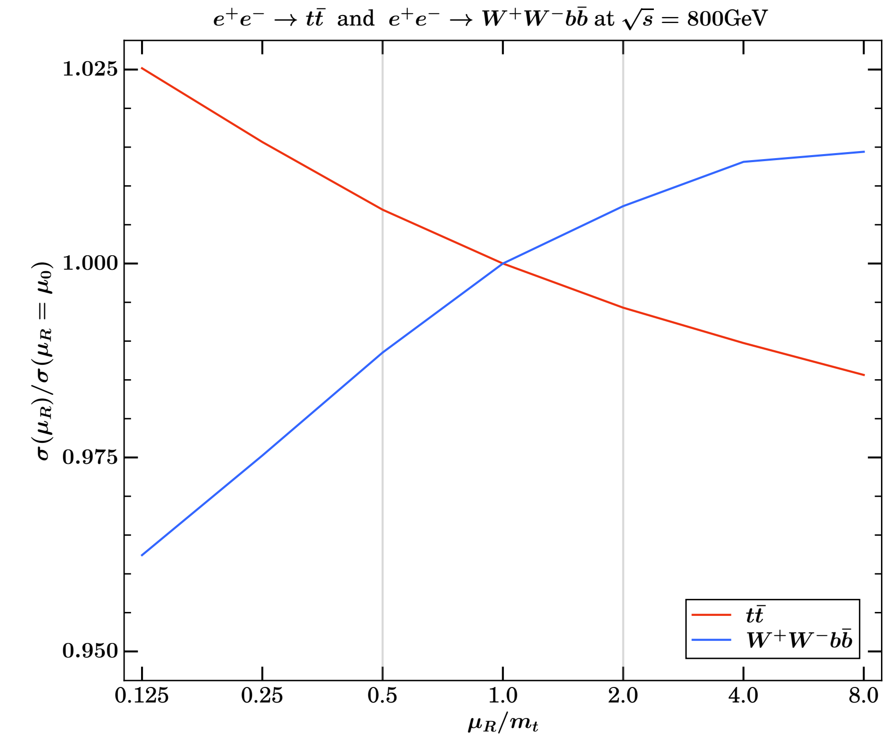
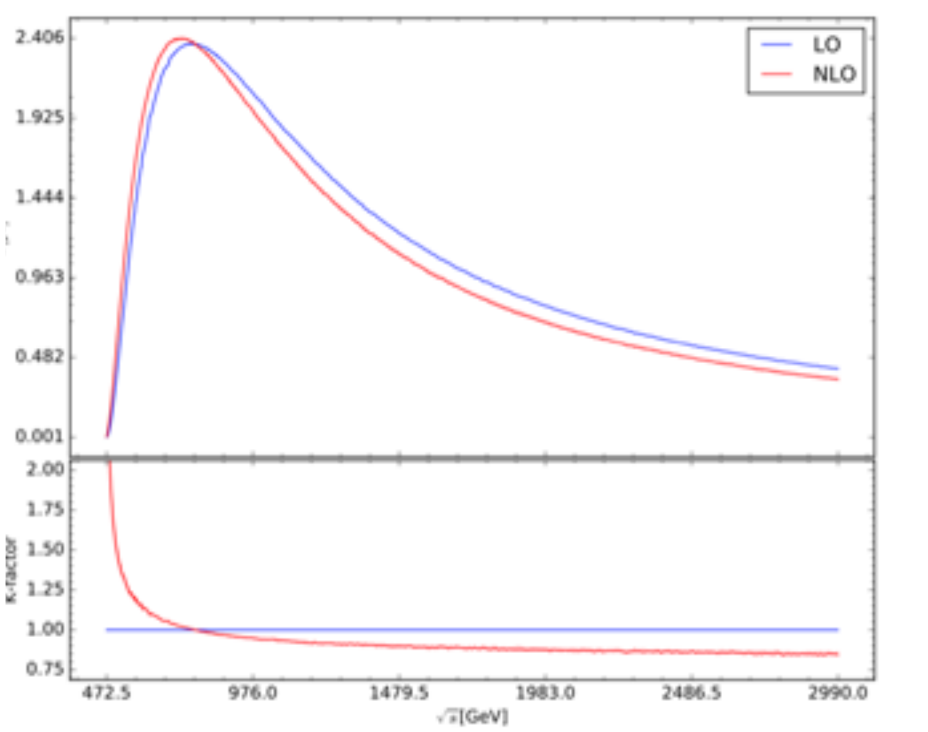
- Typical pentagon diagrams:



NLO QCD Results for *tt* and *ttH*







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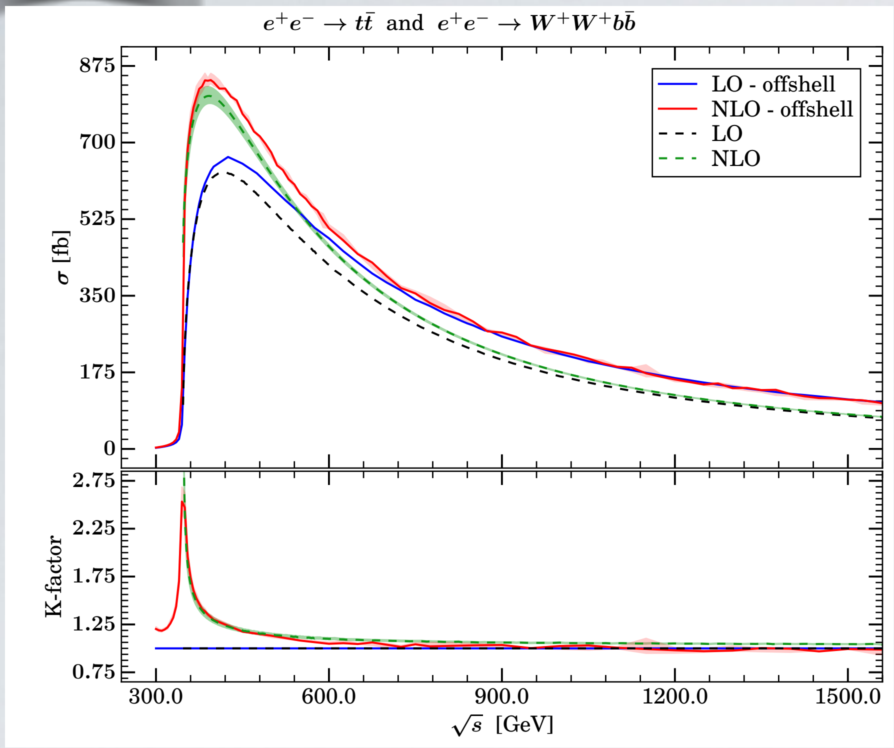

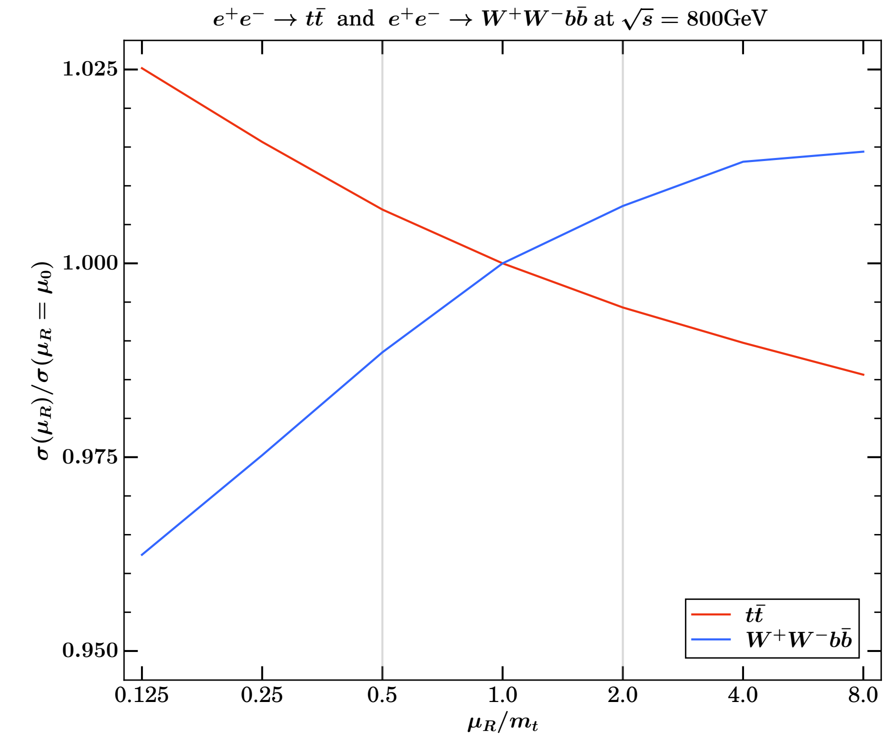

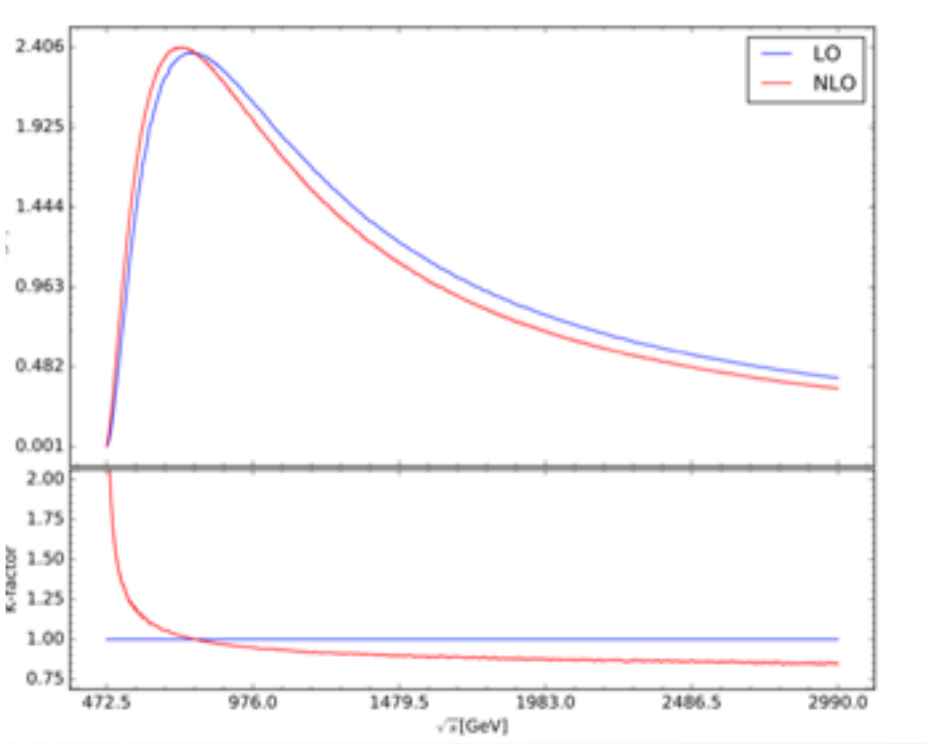

Choose $\sqrt{s}$ = 800 GeV because its the maximum of the *ttH* cross section

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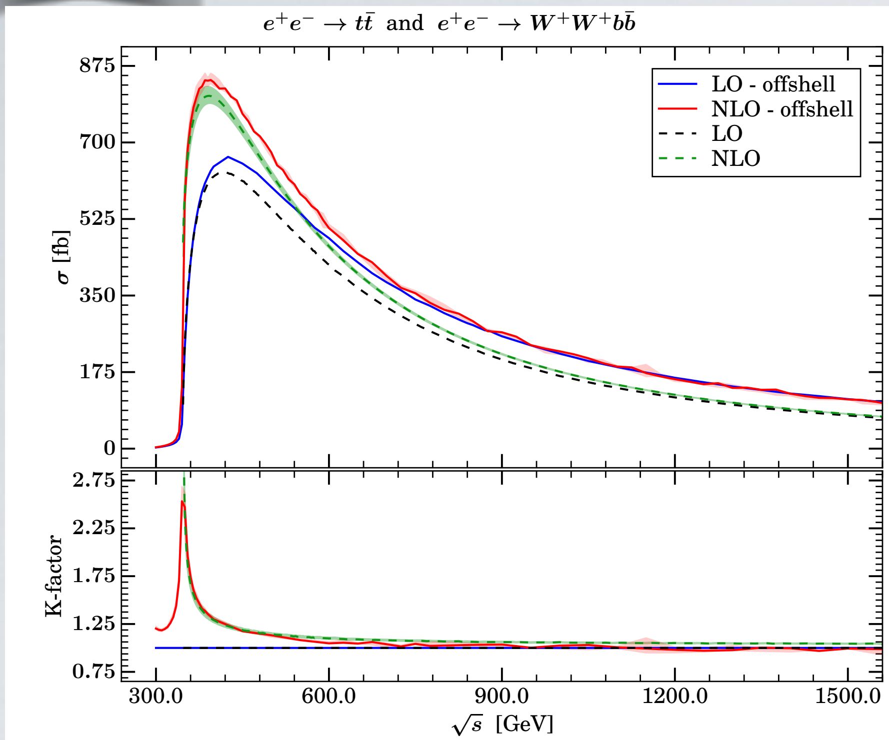

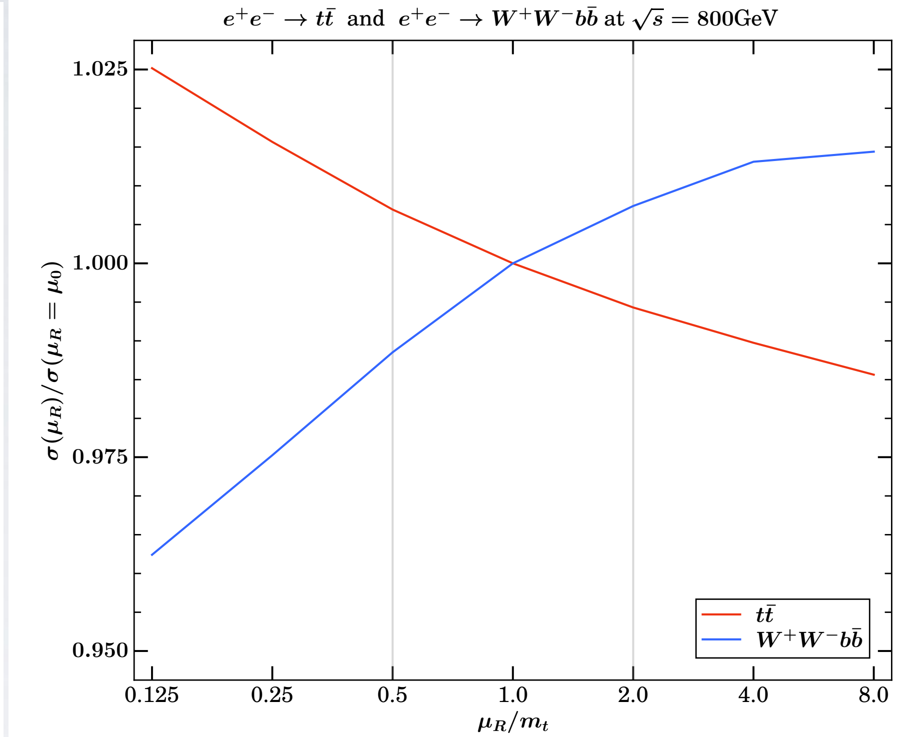

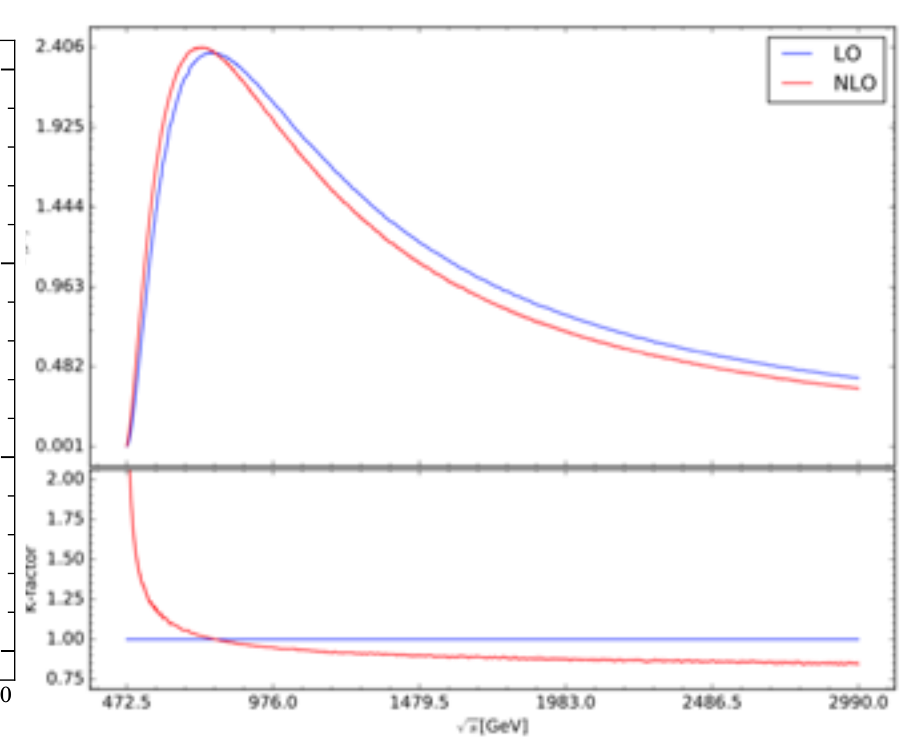

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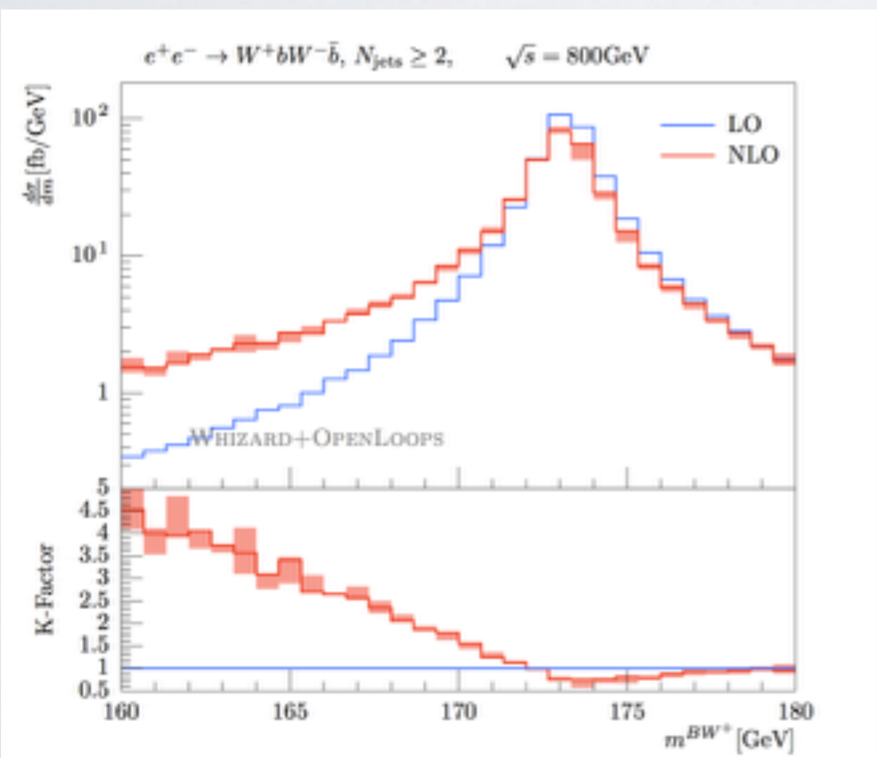

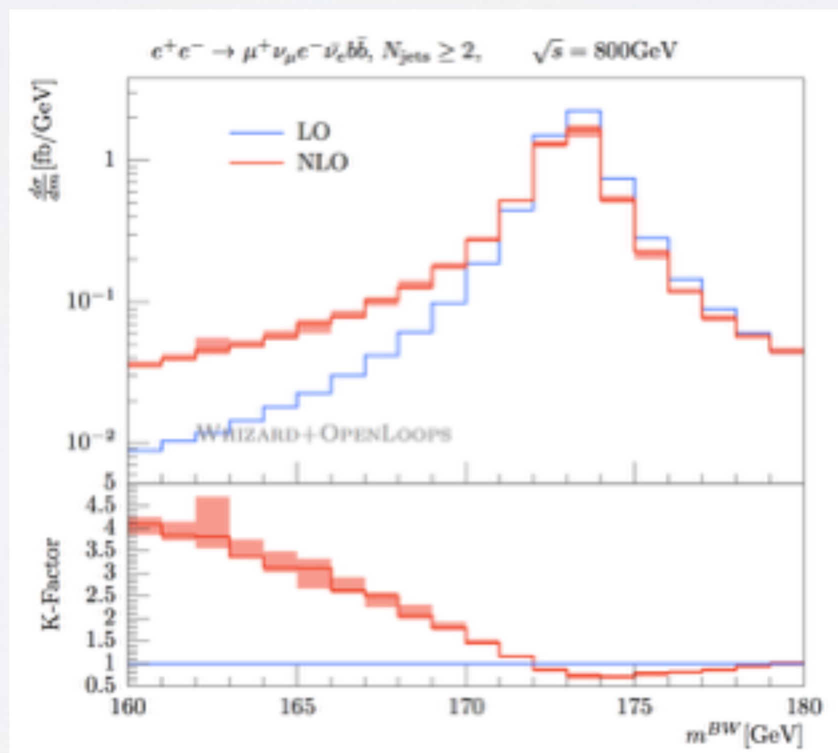

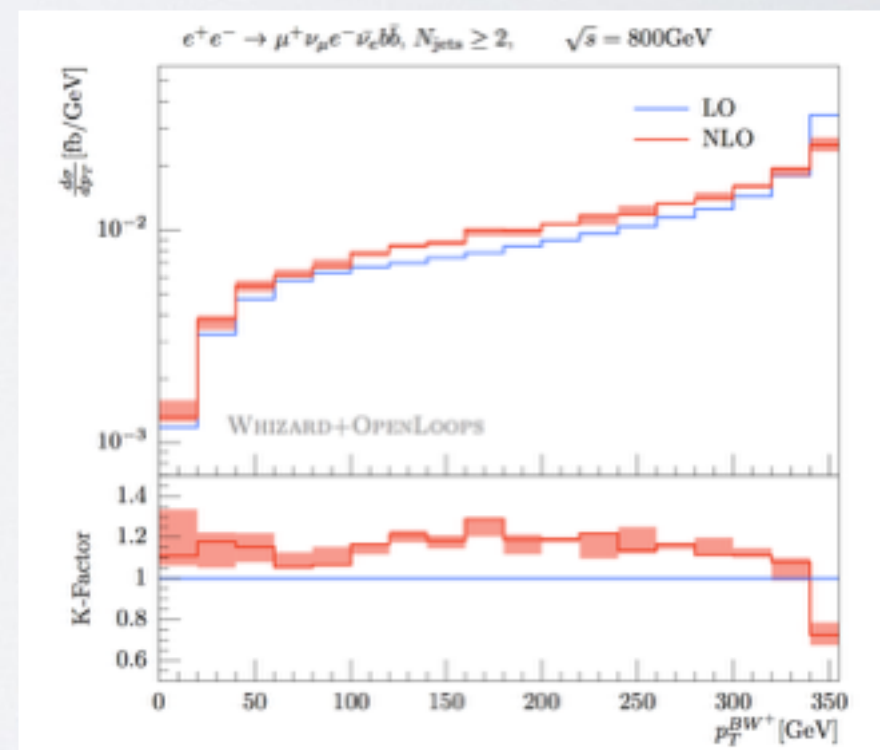

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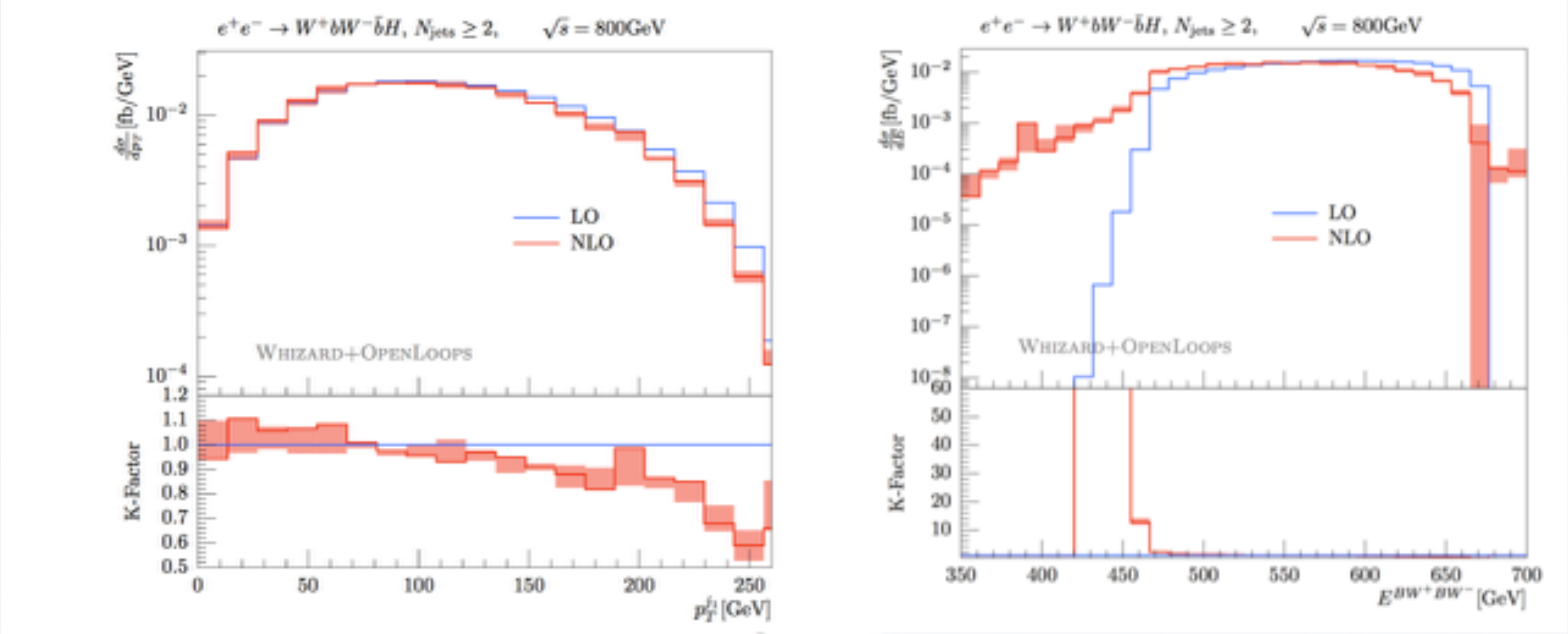

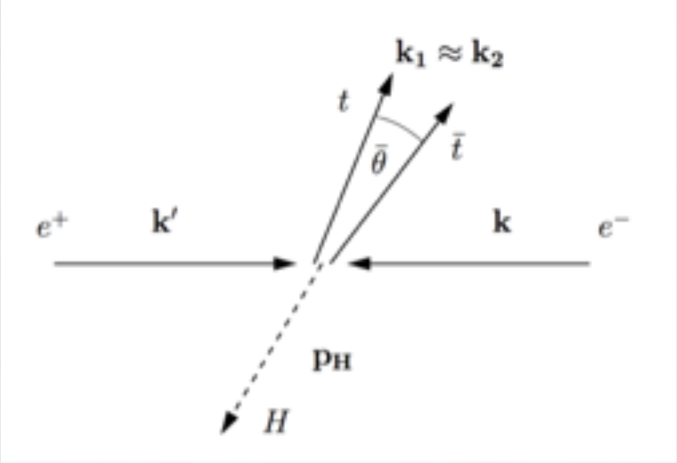

$$E_h = \frac{1}{2\sqrt{s}} \left[s + M_h^2 - (k_1 + k_2)^2 \right]$$

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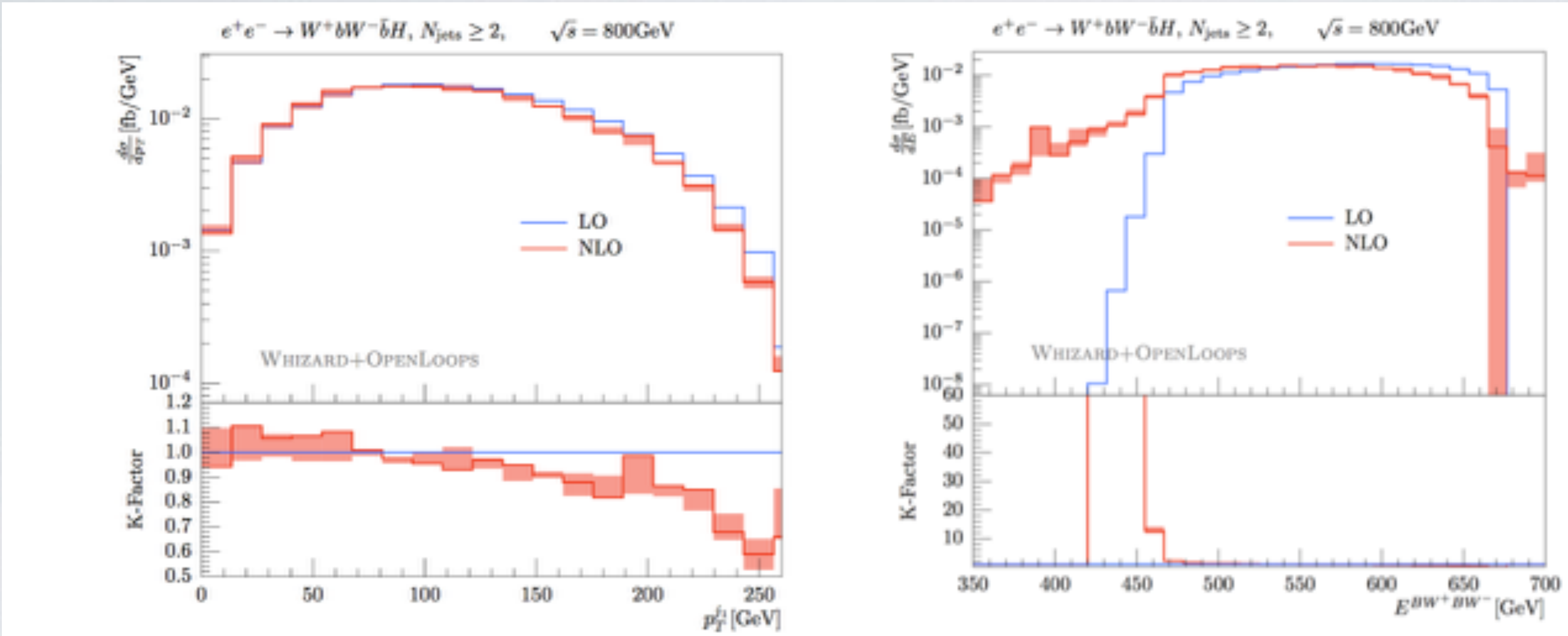

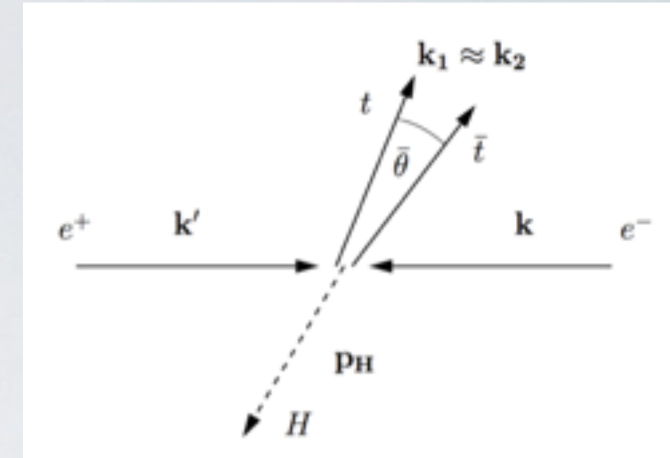

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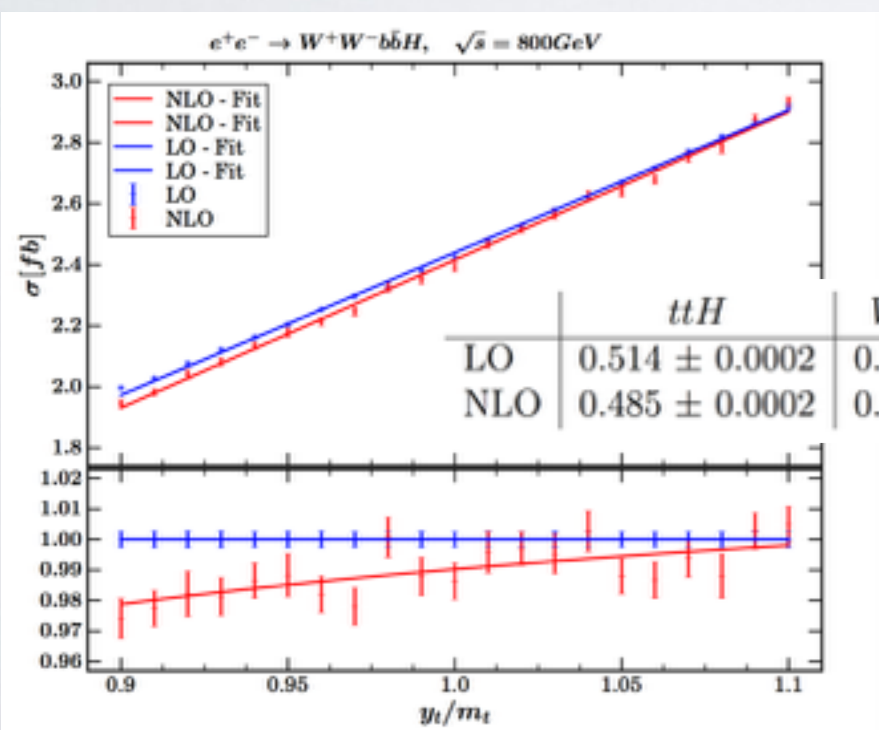
Determination of top Yukawa coupling (*ttH*)



	$t\bar{t}H$	$W^+W^-b\bar{b}H$
LO	0.514 ± 0.0002	0.520 ± 0.001
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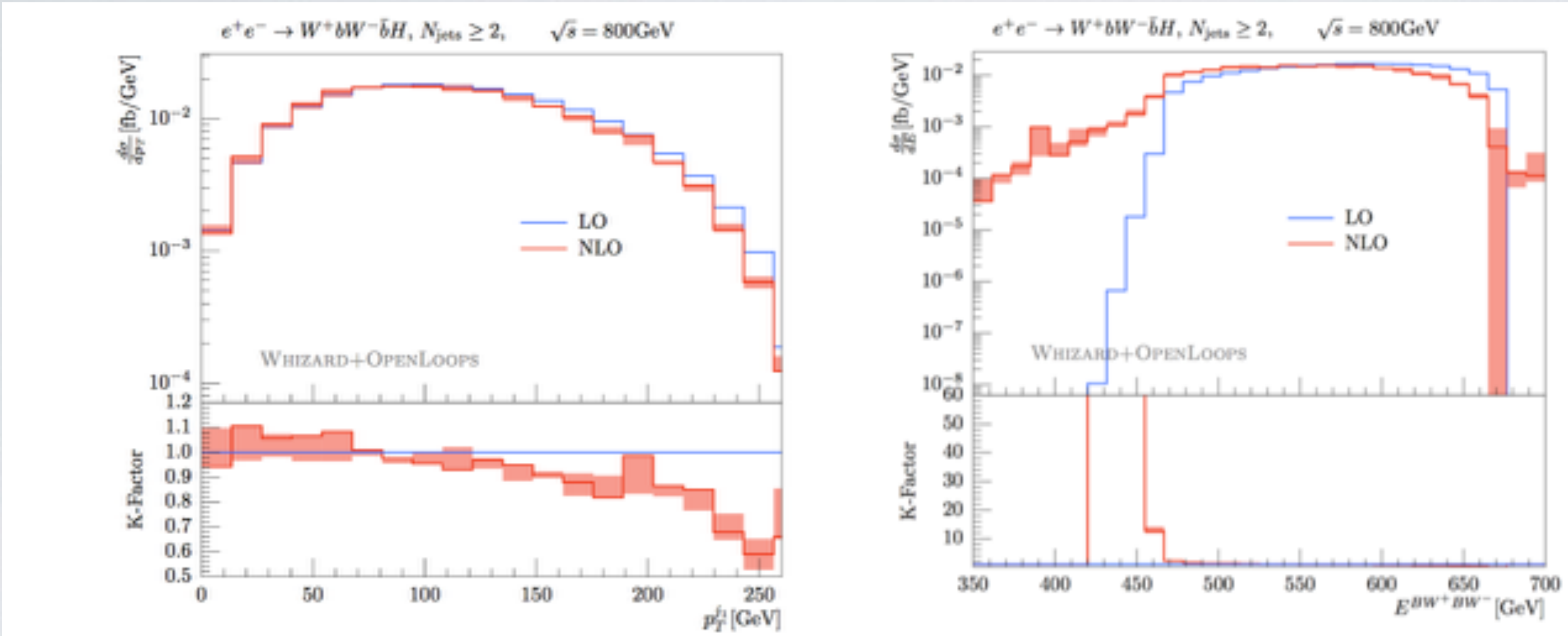

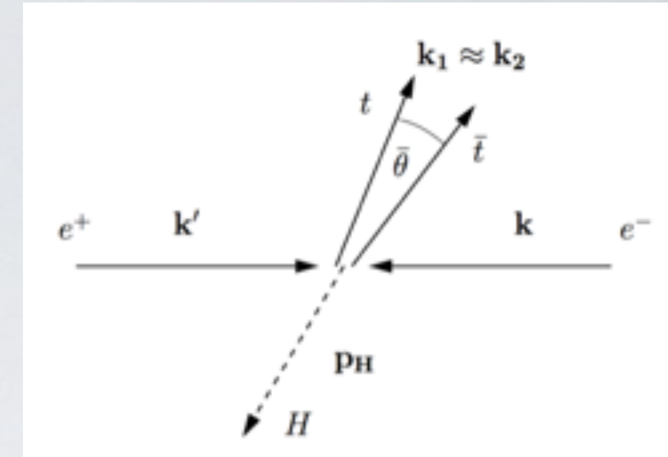

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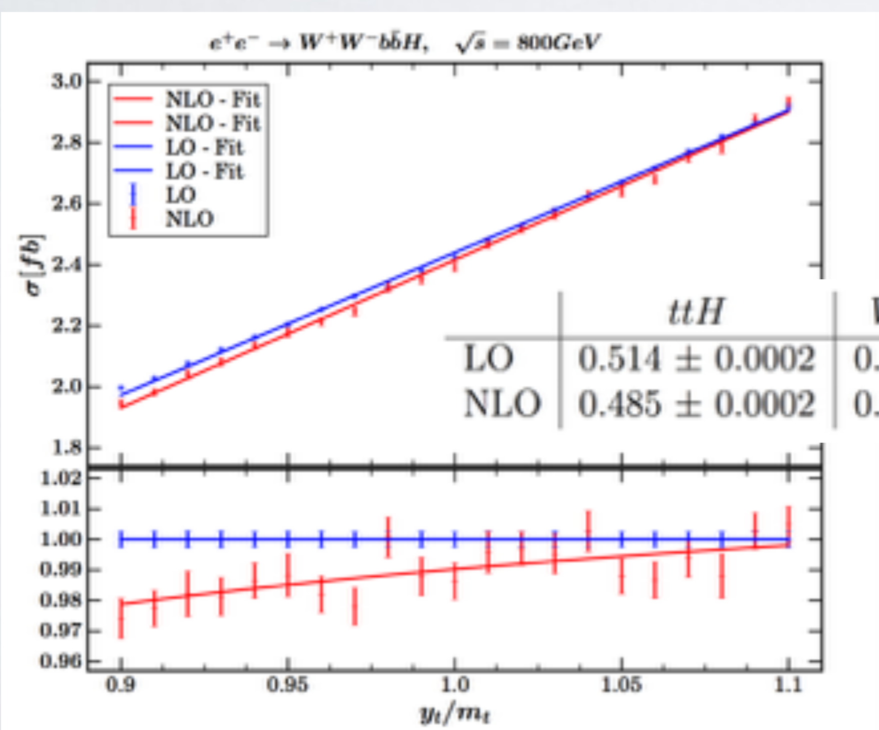

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Polarized Results (*tt*)

- ILC will always run polarized
- Polarized 1-loop amplitudes beyond BLHA

		$\sqrt{s} = 800$ GeV			$\sqrt{s} = 1500$ GeV		
$P(e^-)$	$P(e^+)$	σ^{LO}[fb]	σ^{NLO}[fb]	K-factor	σ^{LO}[fb]	σ^{NLO}[fb]	K-factor
0%	0%	253.7	272.8	1.075	75.8	79.4	1.049
-80%	0%	176.5	190.0	1.077	98.3	103.1	1.049
+80%	0%	176.5	190.0	1.077	53.2	55.9	1.049
-80%	30%	420.8	452.2	1.074	124.9	131.0	1.048
-80%	60%	510.7	548.7	1.074	151.6	158.9	1.048
80%	-30%	208.4	224.5	1.077	63.0	66.1	1.049
80%	-60%	240.3	258.9	1.077	72.7	76.3	1.049

Top-Forward Backward Asymmetry

$$A_{FB} = \frac{\sigma(\cos\theta_t > 0) - \sigma(\cos\theta_t < 0)}{\sigma(\cos\theta_t > 0) + \sigma(\cos\theta_t < 0)}.$$

Gluon emission symmetric in θ ⇒

NLO QCD corrections small

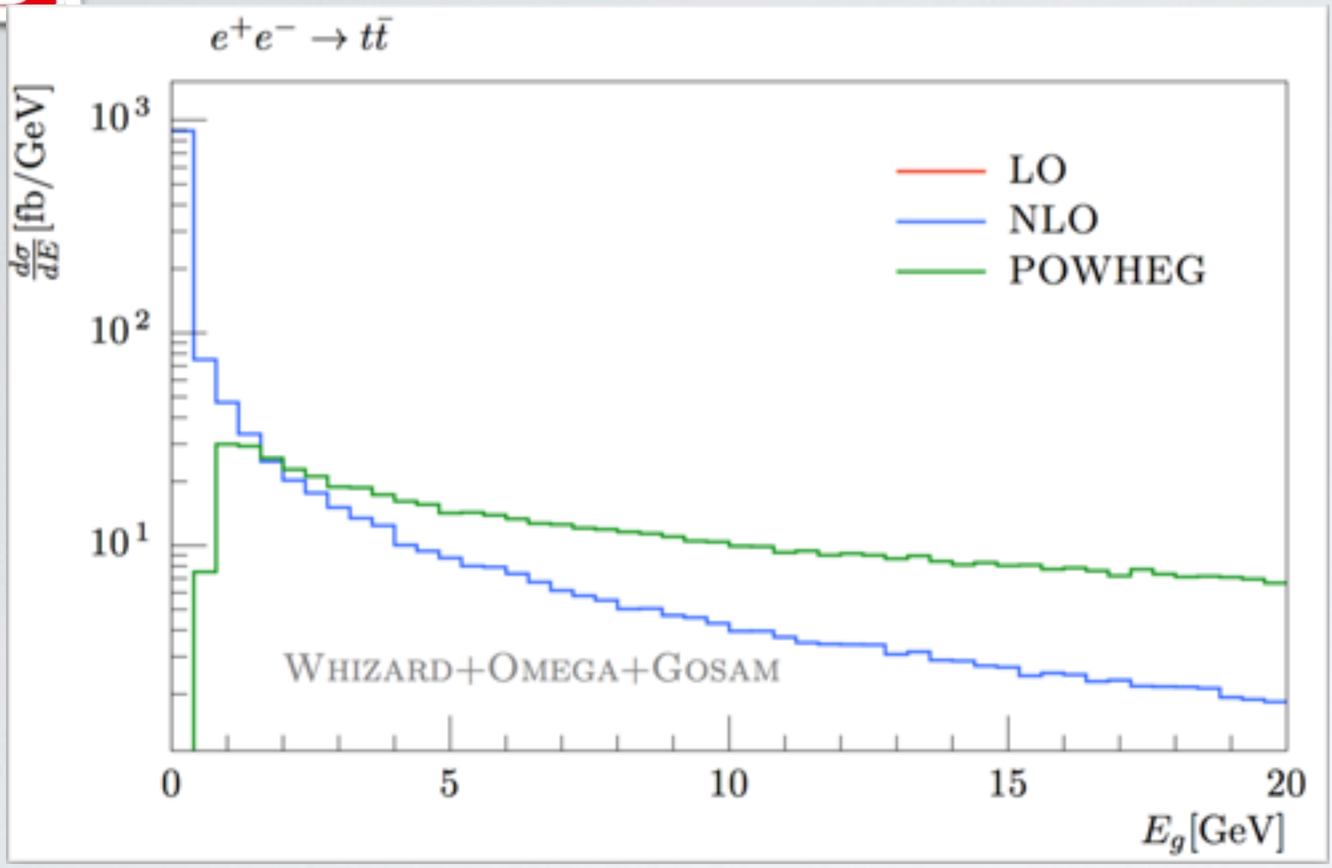
A_{FB} of the top quark

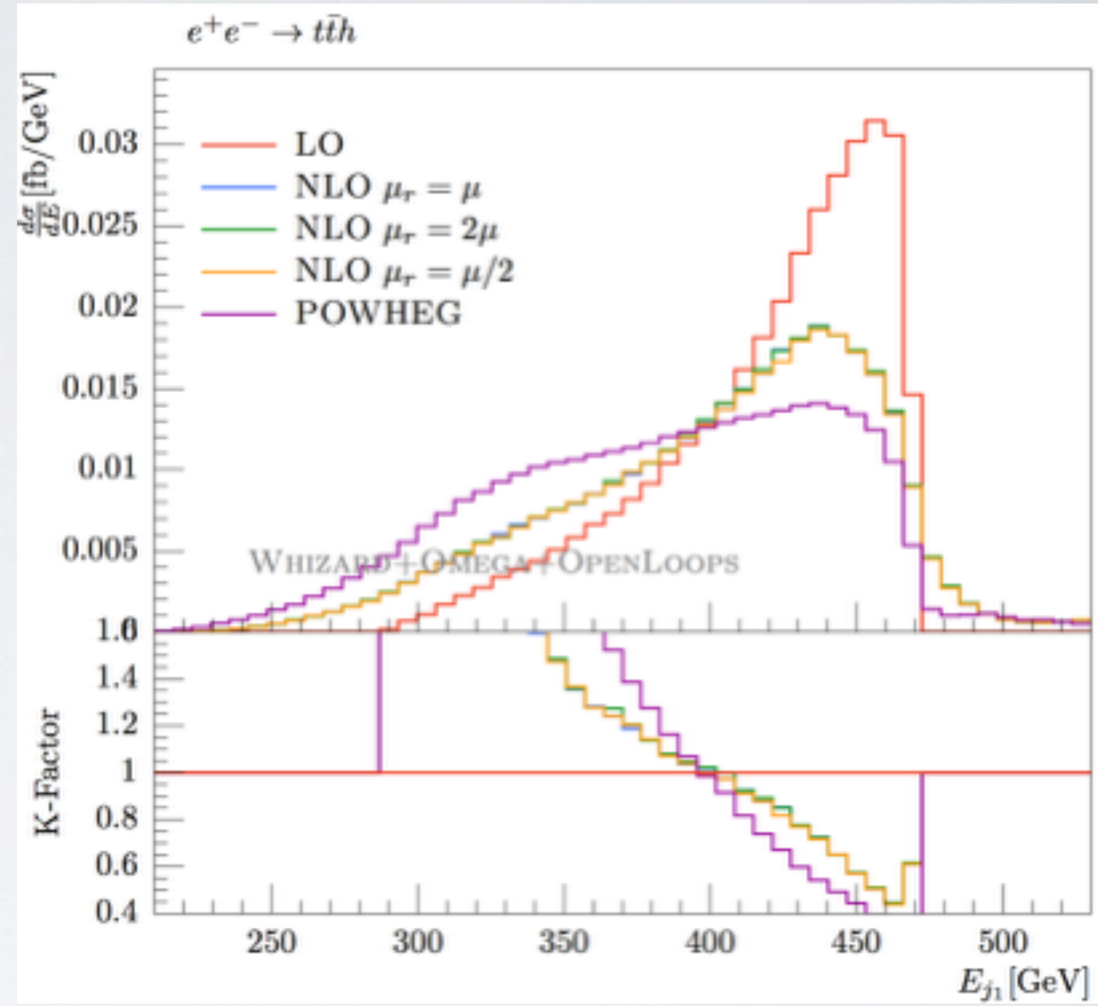
Final state	A_{FB}^{LO}	A_{FB}^{NLO}
$t\bar{t}$	-0.5935 ± 0.0017	-0.5983 ± 0.0048
$W^+W^-b\bar{b}$	-0.4847 ± 0.0017	-0.4778 ± 0.0114
$\mu^+e^-\nu_\mu\bar{\nu}_e b\bar{b}$	-0.5005 ± 0.0001	-0.4947 ± 0.0088
$\mu^+e^-\nu_\mu\bar{\nu}_e b\bar{b}$, without neutrinos	-0.4854 ± 0.0010	-0.4805 ± 0.0089

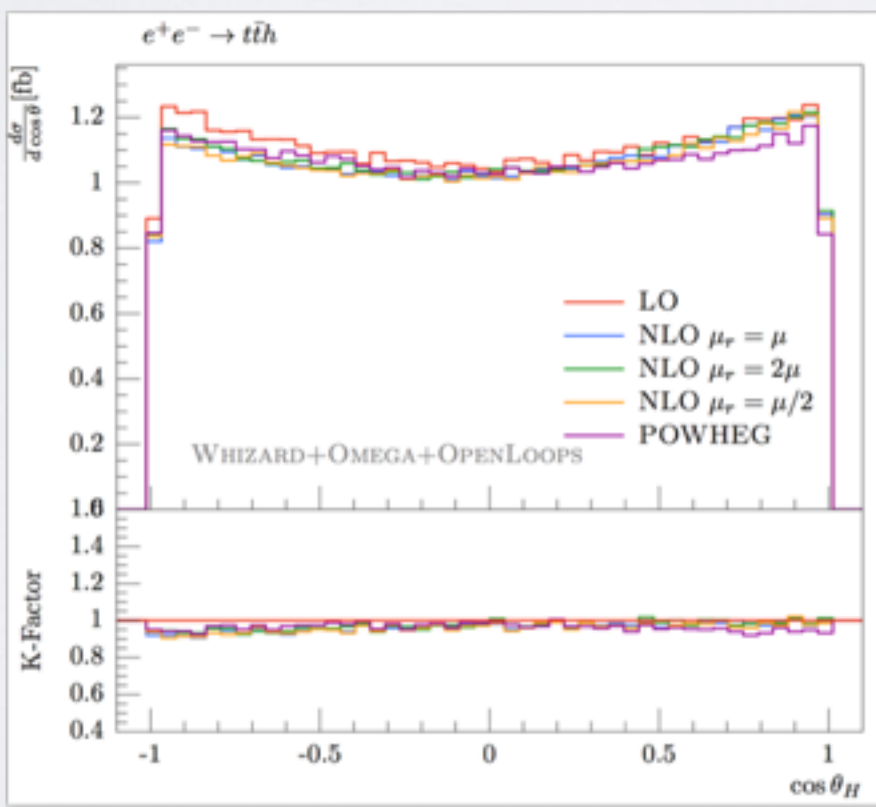
A_{FB} of the anti-top quark

Final state	A_{FB}^{LO}	A_{FB}^{NLO}
$t\bar{t}$	0.4764 ± 0.0017	0.4789 ± 0.0047
$W^+W^-b\bar{b}$	0.3674 ± 0.0017	0.3701 ± 0.0104
$\mu^+e^-\nu_\mu\bar{\nu}_e b\bar{b}$	0.3267 ± 0.0009	0.3264 ± 0.0084
$\mu^+e^-\nu_\mu\bar{\nu}_e b\bar{b}$, without neutrinos	0.2656 ± 0.0009	0.2603 ± 0.0083

POWHEG-matched results for *tt* and *ttH*





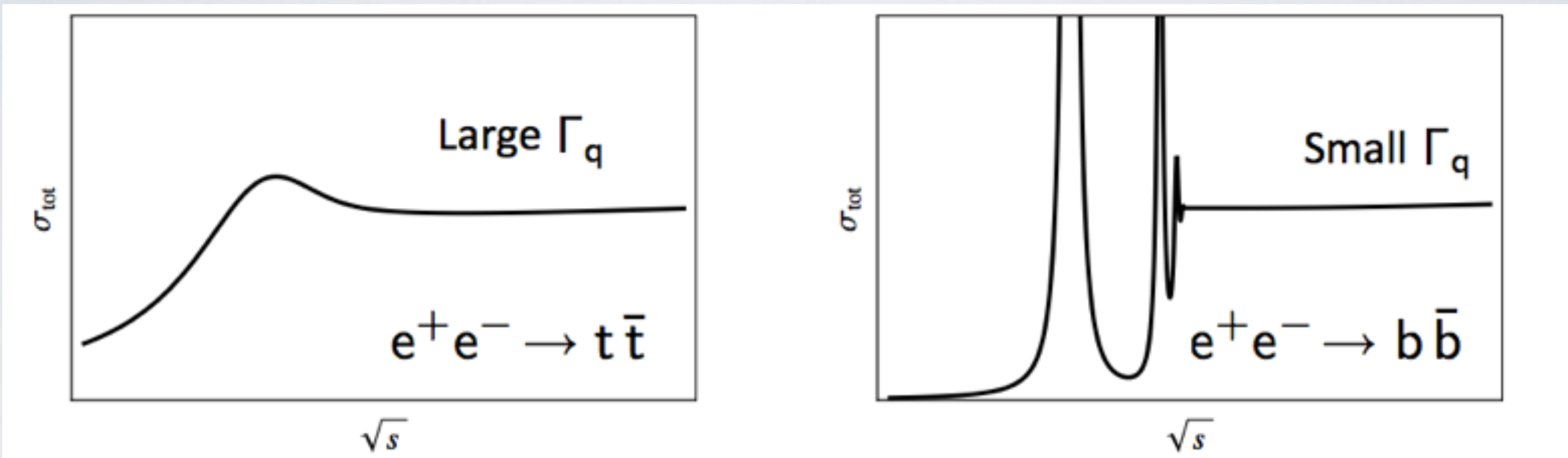


3) Top threshold in (N)LL (p)NRQCD matched to (N)LO QCD in `WHIZARD`

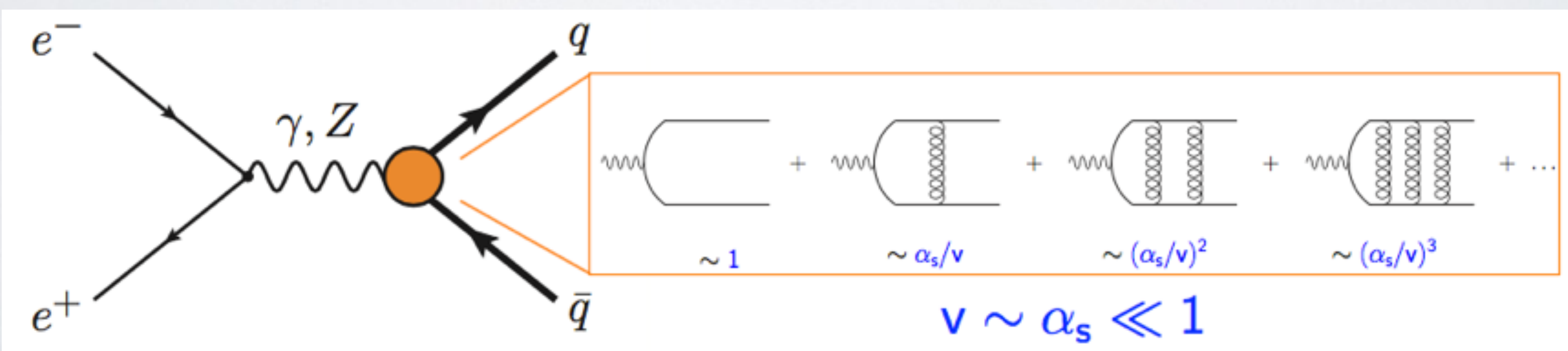
Top Threshold at lepton colliders

ILC top threshold scan best-known method to measure top quark mass, ΔM ~ 30-50 MeV

Heavy quark production at lepton colliders, qualitatively:



Threshold region: top velocity $v \sim \alpha_s \ll 1$



Top Threshold Resummation in (p)NRQCD

- NRQCD is EFT for non-relativistic quark-antiquark systems: separate $M \cdot v$ and $M \cdot v^2$
- Integrate out hard quark and gluon d.o.f.
- Resummation of singular terms close to threshold ($v = 0$) Hoang/Teubner, 1999; Hoang et al., 2001

Phase space of two massive particles

$$R \equiv \frac{\sigma_{t\bar{t}}}{\sigma_{\mu\mu}} = v \sum_k \left(\frac{\alpha_s}{v}\right)^k \sum_i (\alpha_s \ln v)^i \times$$
$$\times \left\{1\,(\mathrm{LL});\ \alpha_s, v\,(\mathrm{NLL});\ \alpha_s^2, \alpha_s v, v^2\,(\mathrm{NNLL})\right\}$$

(p/v)NRQCD EFT w/ RG improvement

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$$R^{\gamma,Z}(s) = \underbrace{F^v(s) R^v(s)}_{\text{s-wave: LL+NLL}} + \underbrace{F^a(s) R^a(s)}_{\text{p-wave}\sim v^2\text{:NNLL}}$$

but contributes
at NLL differentially!

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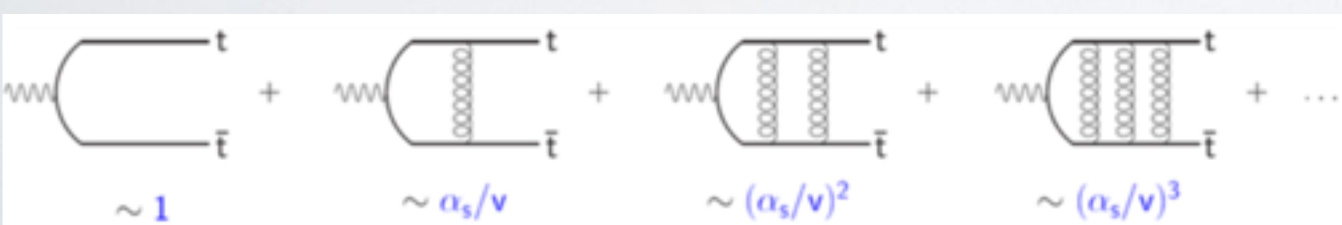
Coulomb potential gluon ladder resummation



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but contributes
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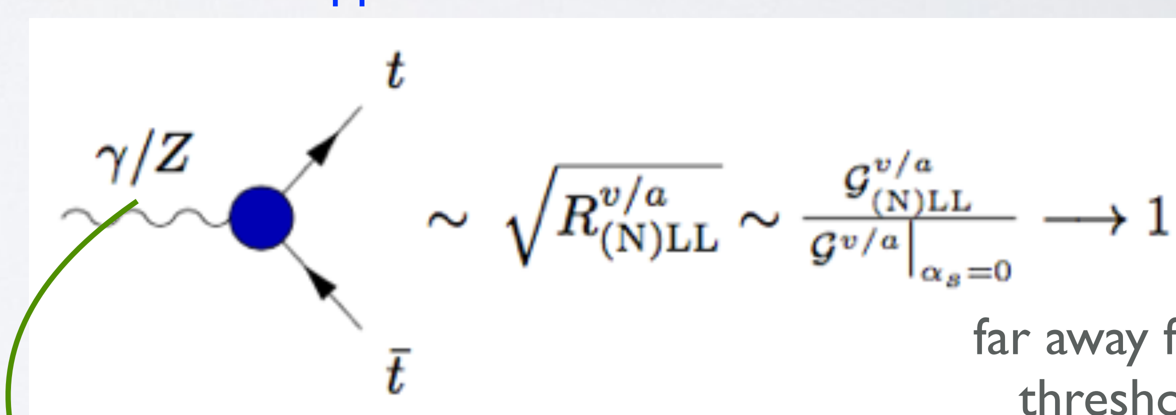
can be mapped onto effective *ttV* vertex



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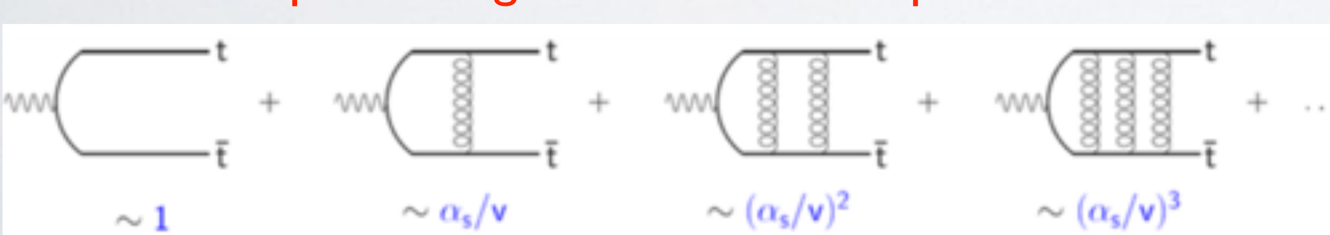


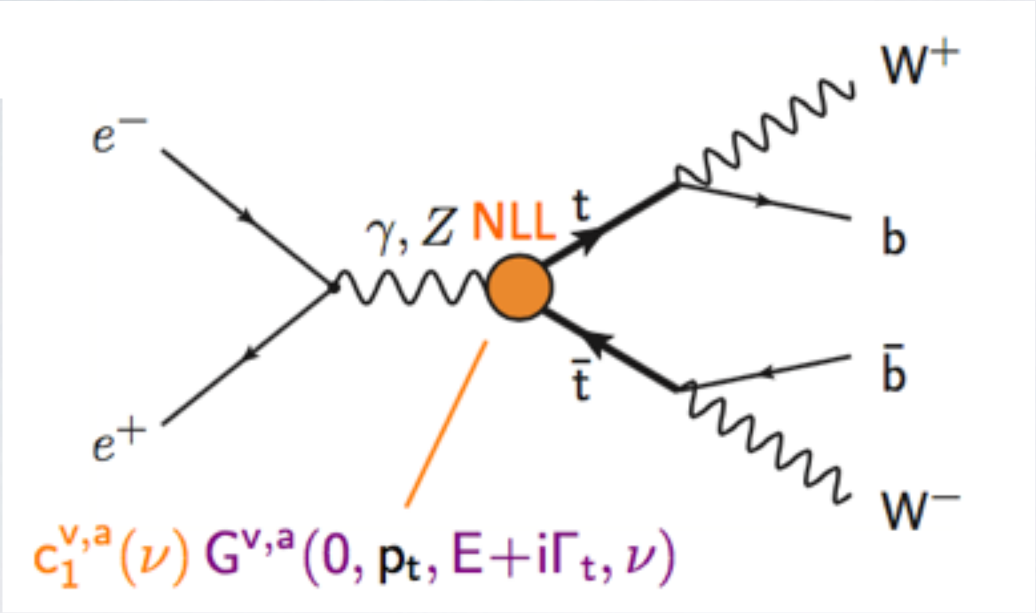
$$\mathbb{C} \ni \mathcal{G}^{v/a}_{\mathrm{(N)LL}} = \mathcal{G}^{v/a}_{\mathrm{(N)LL}}(\alpha_s, M_t^{\mathrm{pole}}, \sqrt{s}, |\vec{p}_t|, \Gamma_t)$$

differential in off-shell *tt* phase space

Top Threshold in WHIZARD

with B. Chokoufé/A. Hoang/M. Stahlhofen/T. Teubner/C. Weiss

- Implement resummed threshold effects as effective vertex [form factor] in WHIZARD
- $G^{v,a}(0, p_t, E + i\Gamma_t, \nu)$ from TOPPIK code [Jezabek/Teubner], included in WHIZARD



- Default parameters:

$$\mathbf{M^{1S} = 172\,GeV}, \ \Gamma_t = 1.54\,\mathrm{GeV}, \quad \alpha_s(M_Z) = 0.118$$

$$M^{1S} = M_t^{pole}(1 - \Delta_{(Coul.)}^{LL/NLL})$$ Marquard et al.

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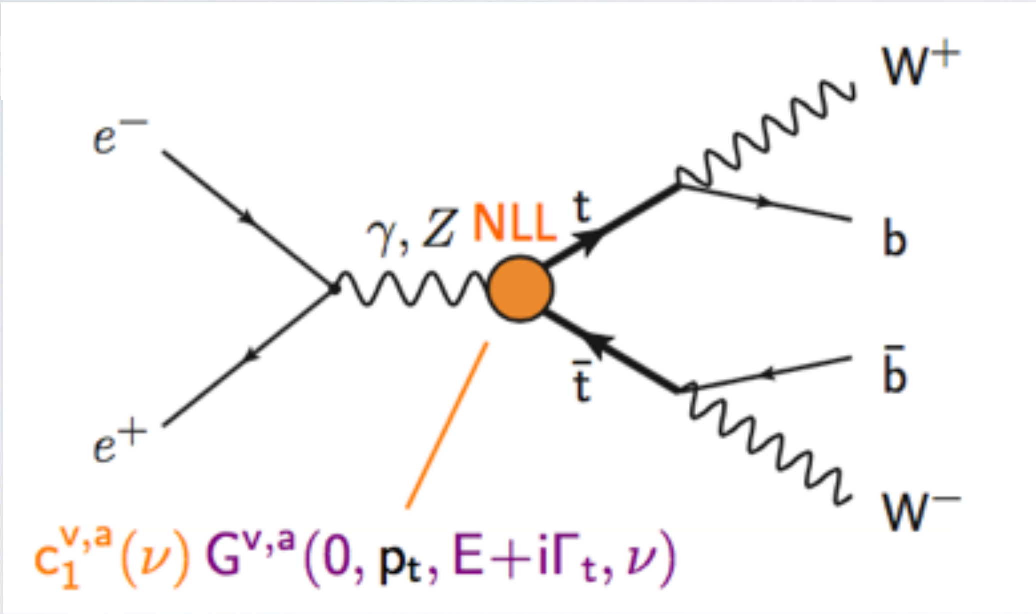

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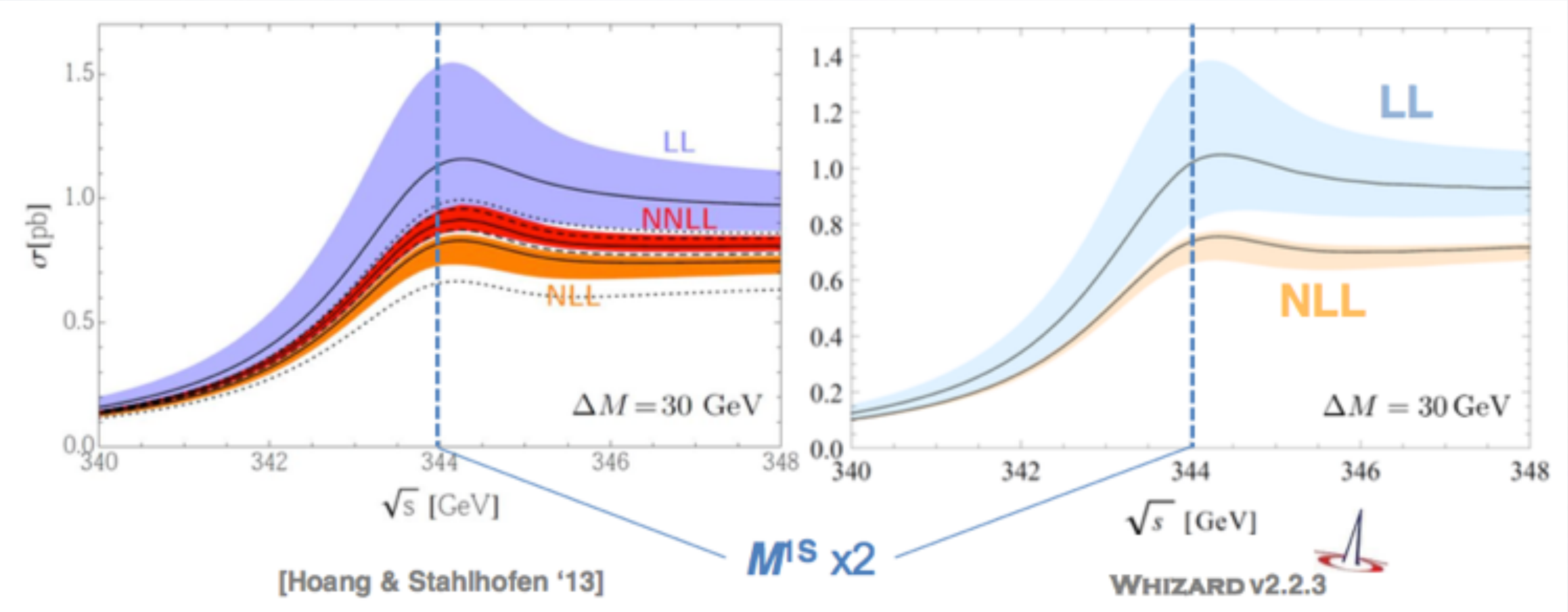

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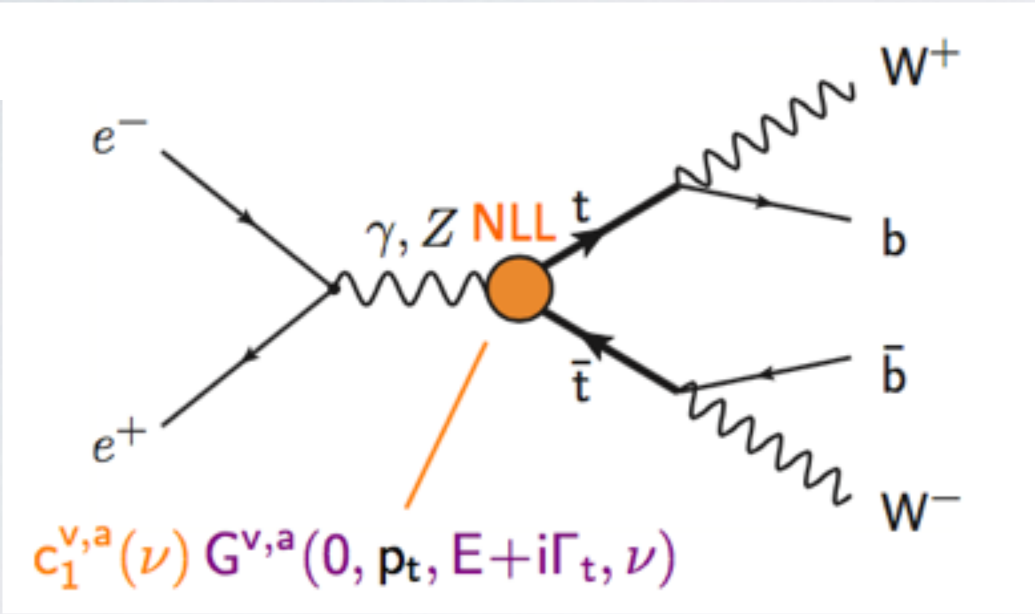

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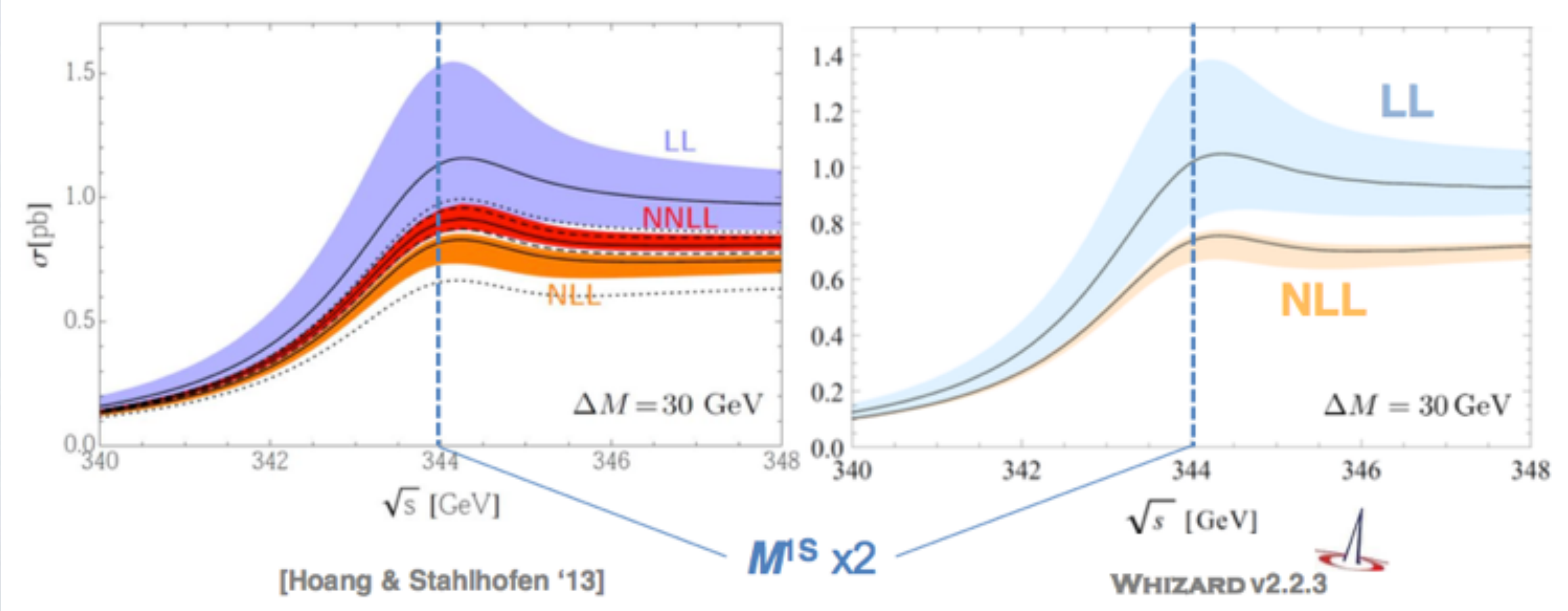
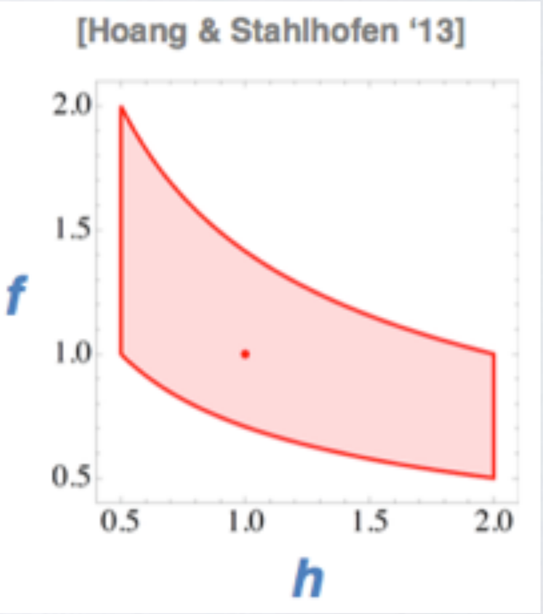
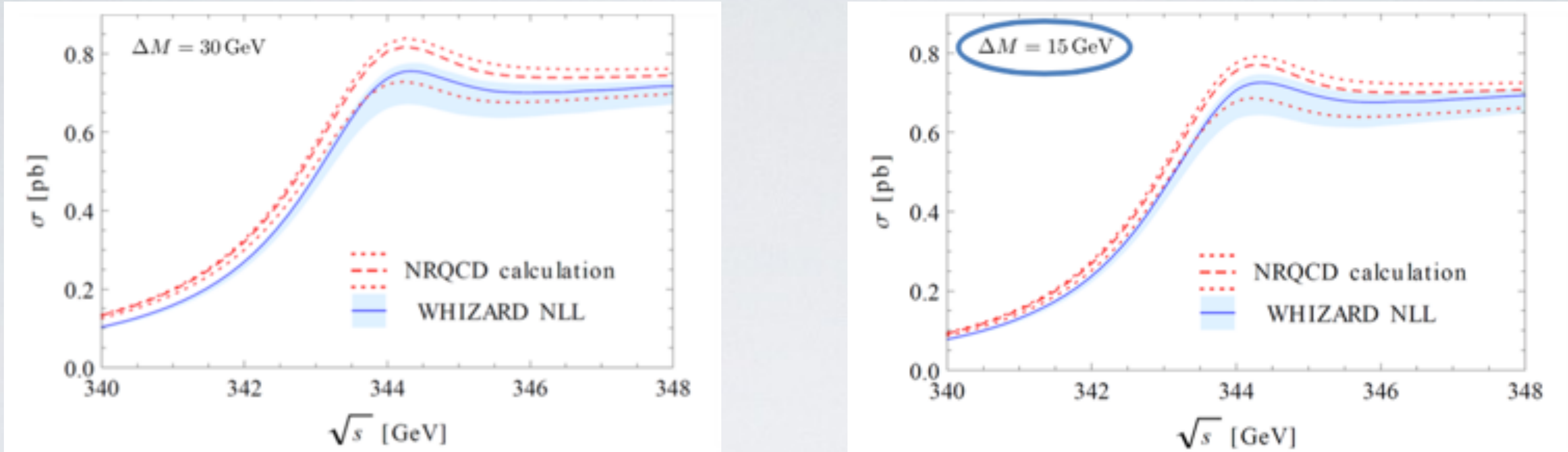
Theory uncertainties from scale variations: hard and soft scale

$$\mu_h = h \cdot m_t \qquad \mu_s = f \cdot m_t v$$





Sanity checks: correct limit for $\alpha_s \longrightarrow 0$, stable against variation of cutoff ΔM [15-30 GeV]



- Why include LL/NLL in a Monte Carlo event generator?
  - Important effects: beamstrahlung; ISR; LO electroweak terms
  - More exclusive observables accessible

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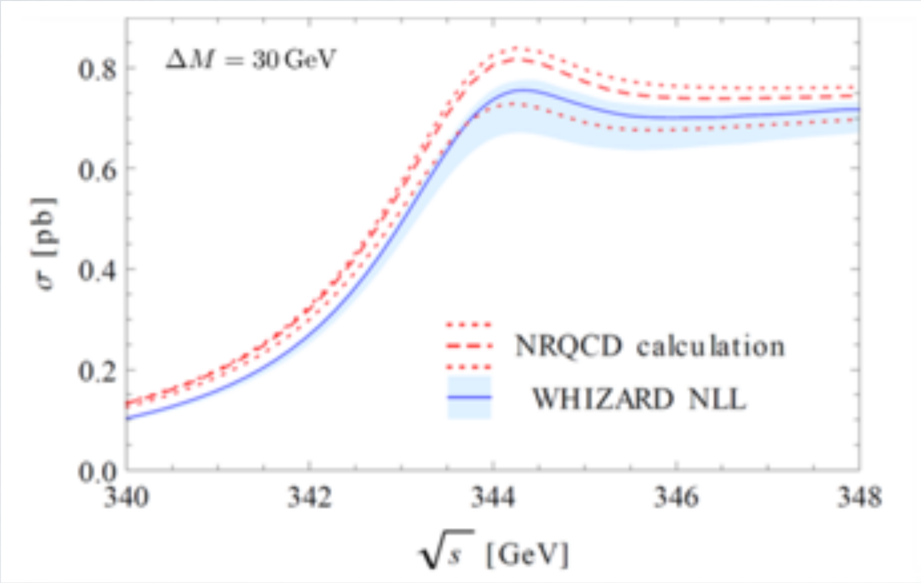

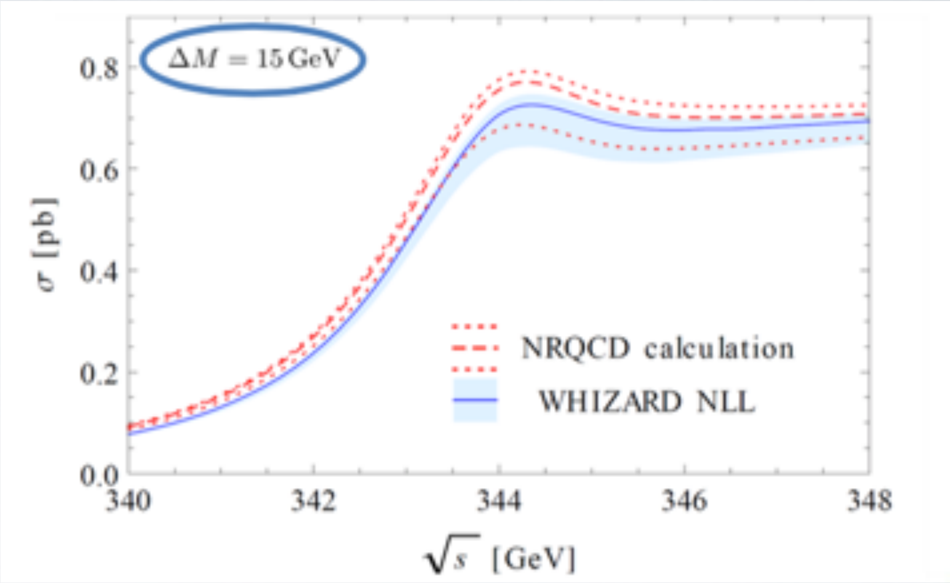

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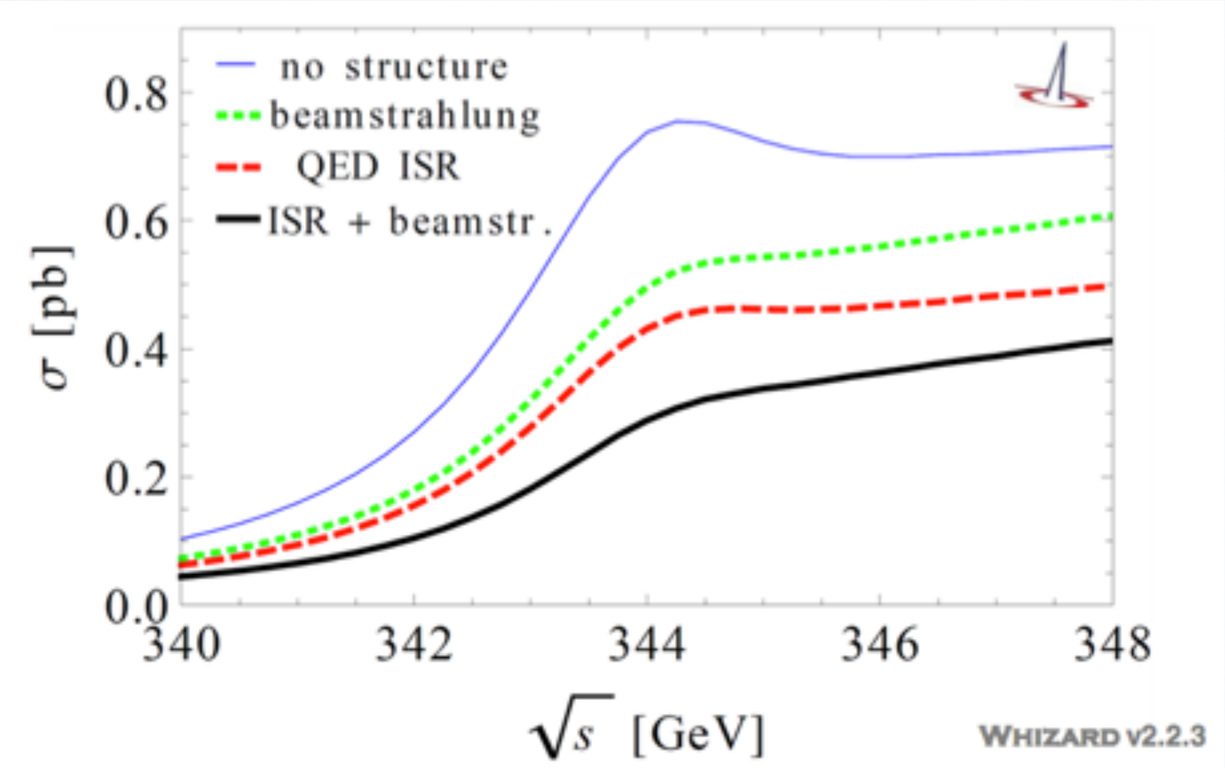

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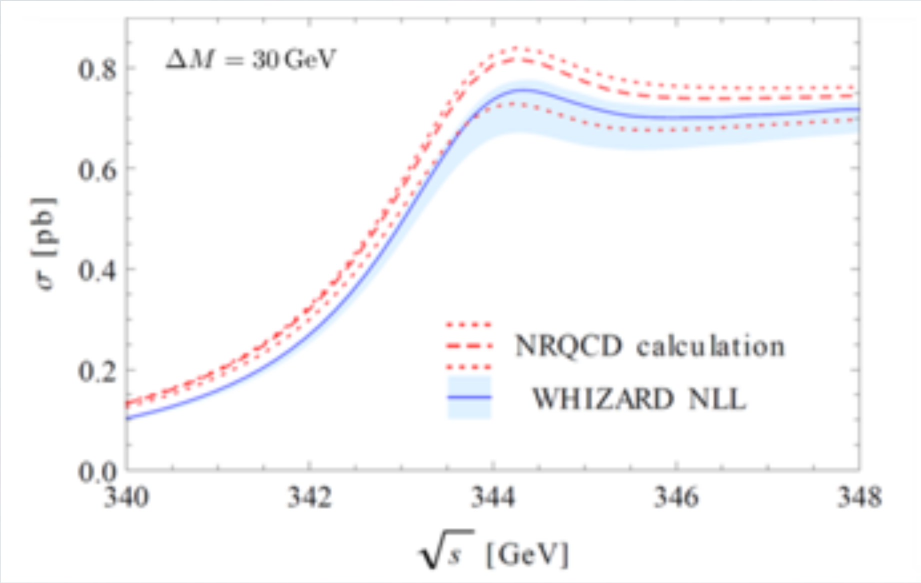

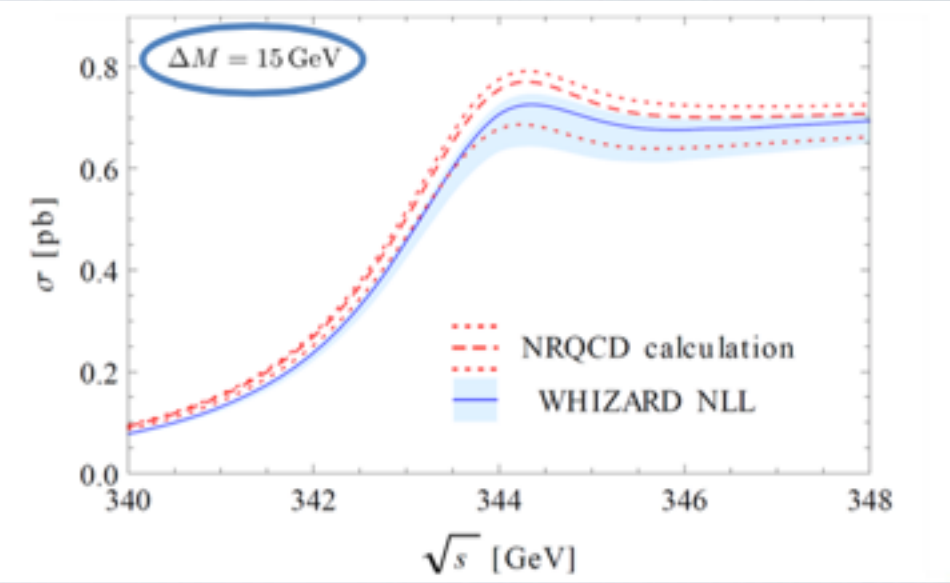

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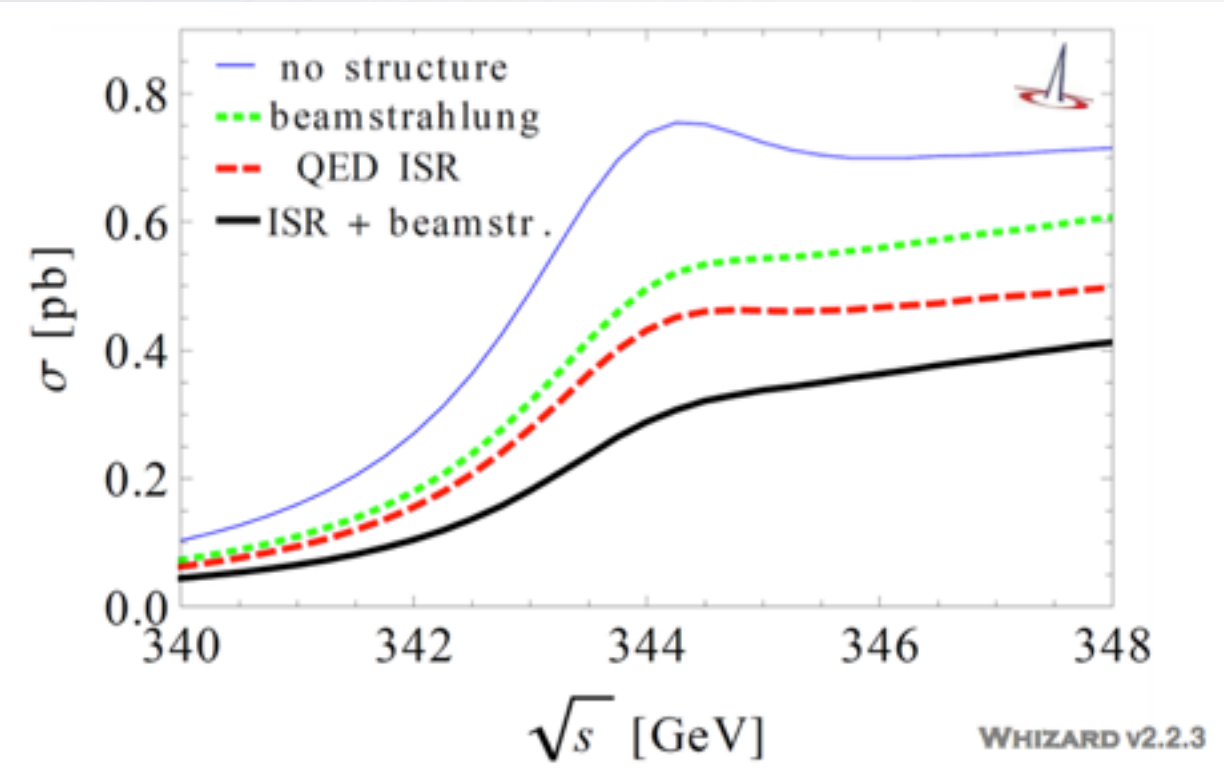
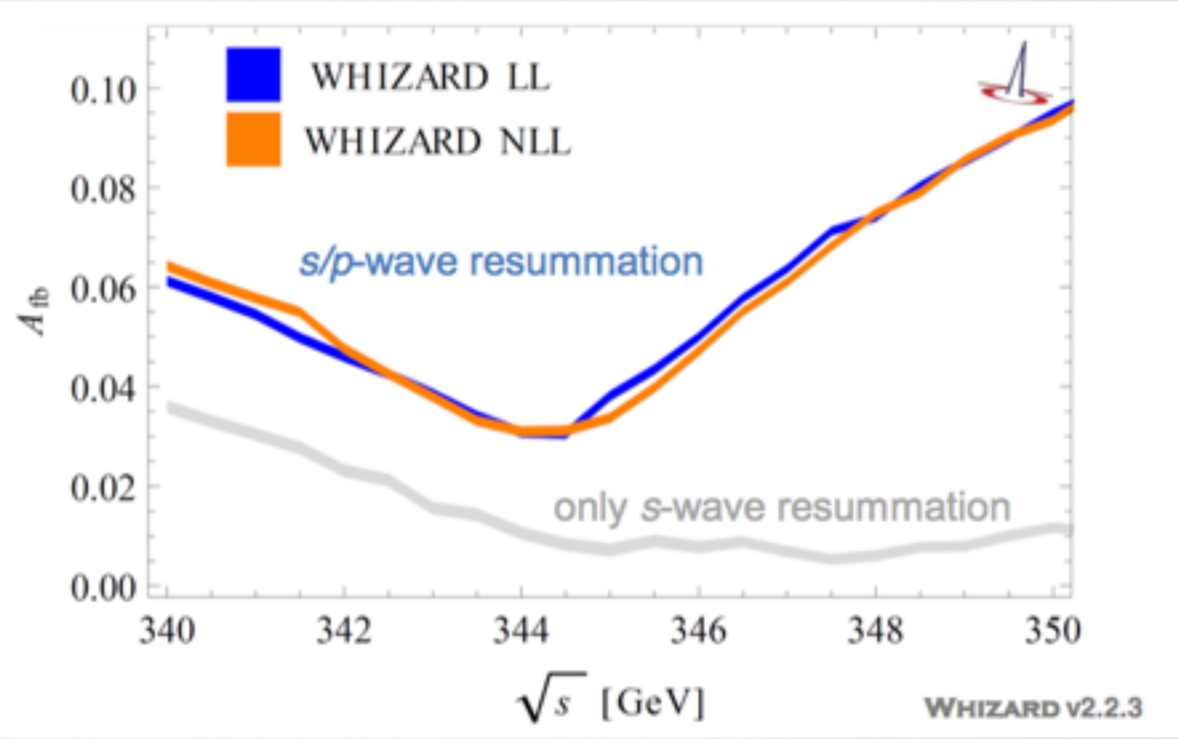
Forward-backward asymmetry (norm. ⇒ good shape stability)

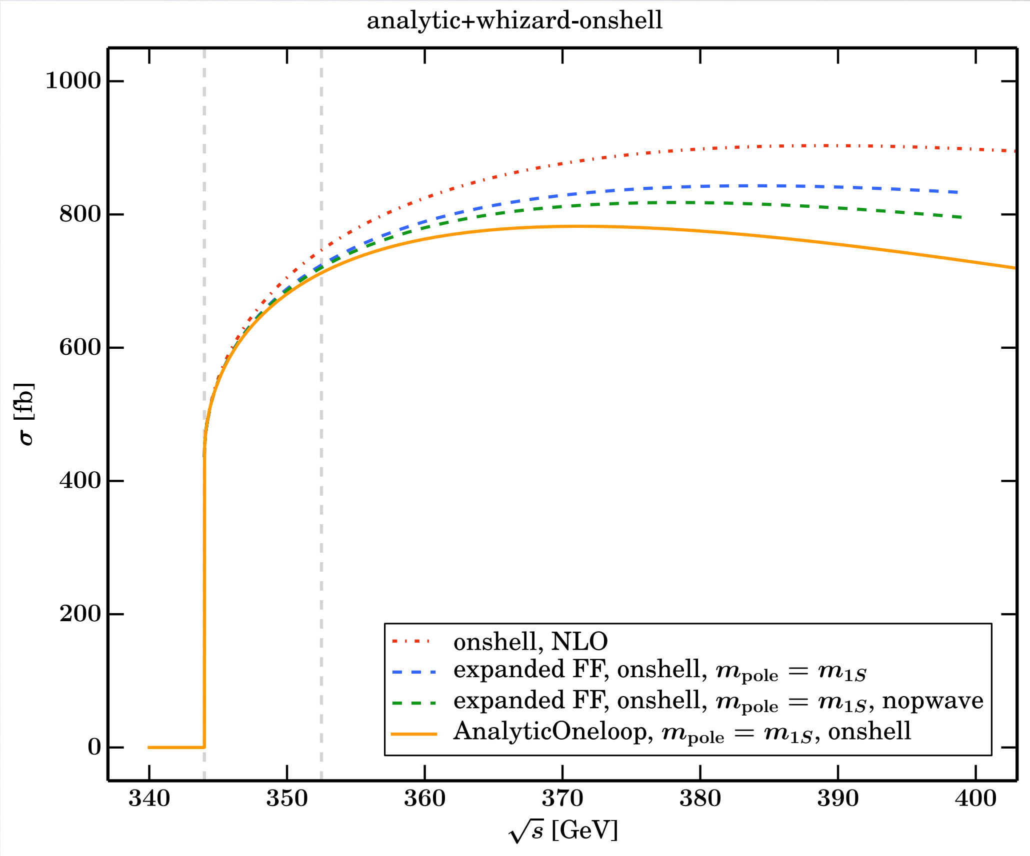
$$A_{fb} := \frac{\sigma(p_z^t > 0) - \sigma(p_z^t) < 0)}{\sigma(p_z^t > 0) + \sigma(p_z^t < 0)}$$





Matching to continuum at (LO and) NLO

- Transition region between relativistic and resummation effects
- CLIC benchmark energies:
  0.38 TeV, 1.4 TeV, 3.0 TeV
- Remove double-counting NLO / (N)LL



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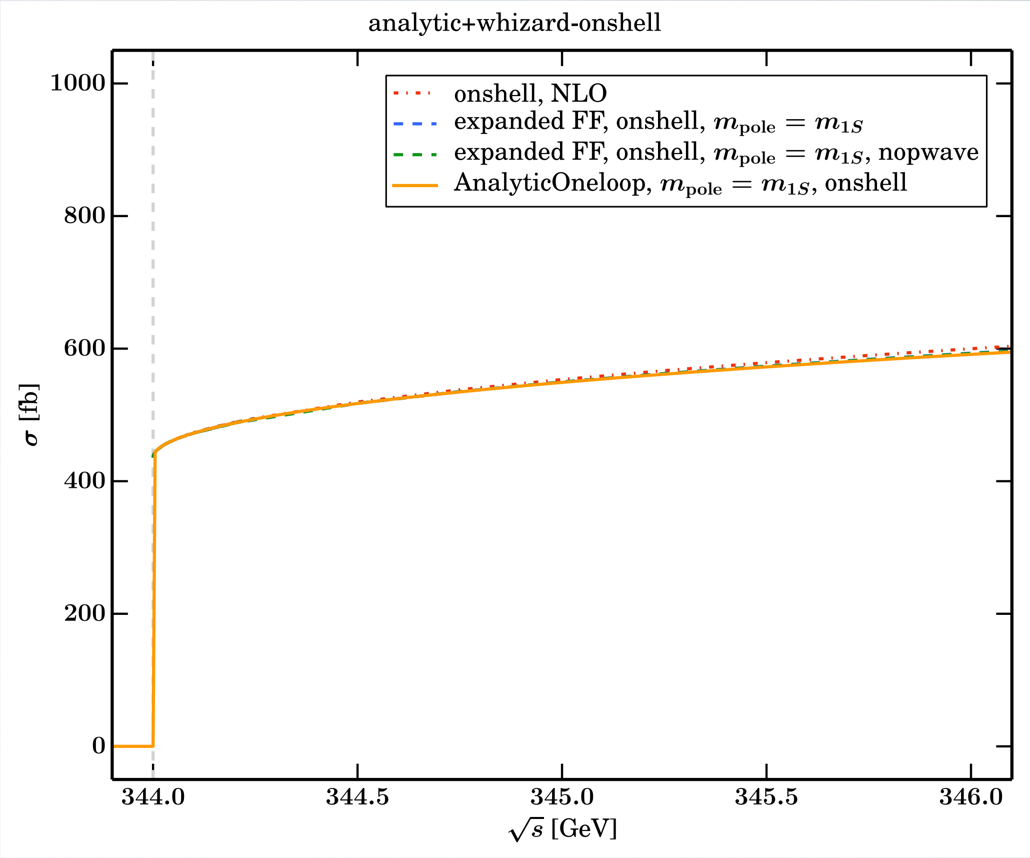

Resummed formfactor, expanded to $\mathcal{O}(\alpha_s)$

$$\nu = \sqrt{\frac{\sqrt{s} - 2m_t + i\Gamma_t}{m}} \qquad p = |\vec{p}| \qquad p_0 = E_t - m_t$$

$$F^{\text{expanded}}[\alpha_{\rm H}, \alpha_{\rm S}] = \alpha_{\rm H}\left(-\frac{2C_F}{\pi}\right) + \alpha_{\rm S}\left(\frac{iC_F m \log\frac{mv+p}{mv-p}}{2p}\right)$$

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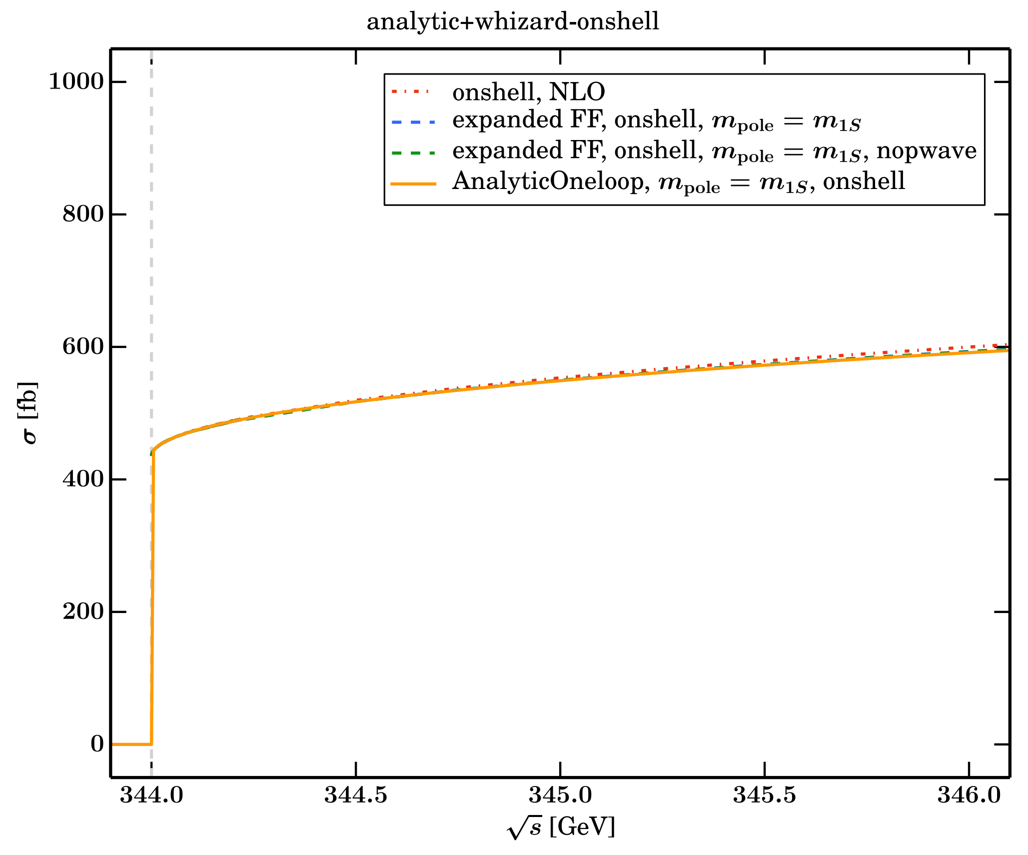

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Matching formula

$$\begin{aligned}\sigma_{\text{matched}} = {} & \sigma_{\text{QCD}}[\alpha_{\text{H}}] - \sigma^{\text{expanded}}_{\text{NRQCD}}[\alpha_{\text{H}},\, \alpha_{\text{H}}] \\ & + \sigma^{\text{expanded}}_{\text{NRQCD}}[\alpha_{\text{H}},\, f_s \alpha_{\text{S}} + (1 - f_s)\,\alpha_{\text{H}}] \\ & + \sigma^{\text{full}}_{\text{NRQCD}}[f_s \alpha_{\text{H}},\, f_s \alpha_{\text{S}},\, f_s \alpha_{\text{US}}] - \sigma^{\text{expanded}}_{\text{NRQCD}}[f_s \alpha_{\text{H}},\, f_s \alpha_{\text{S}}]\end{aligned}$$

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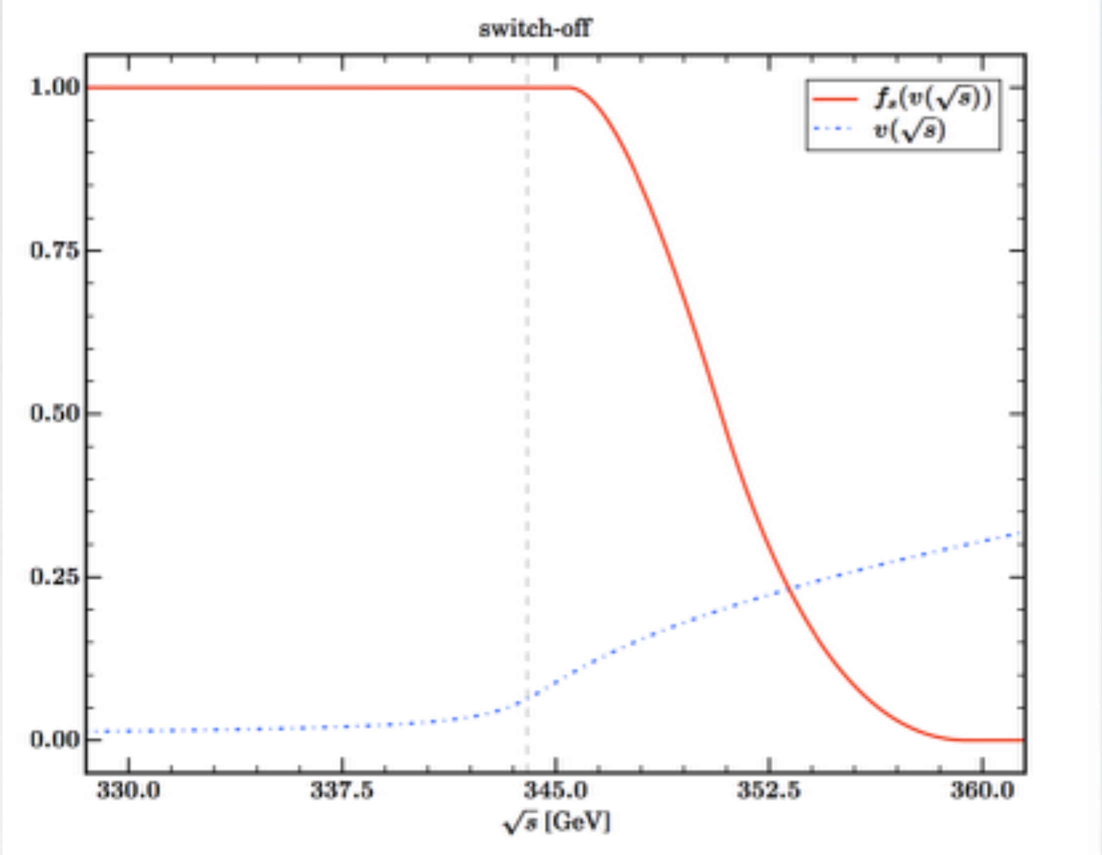

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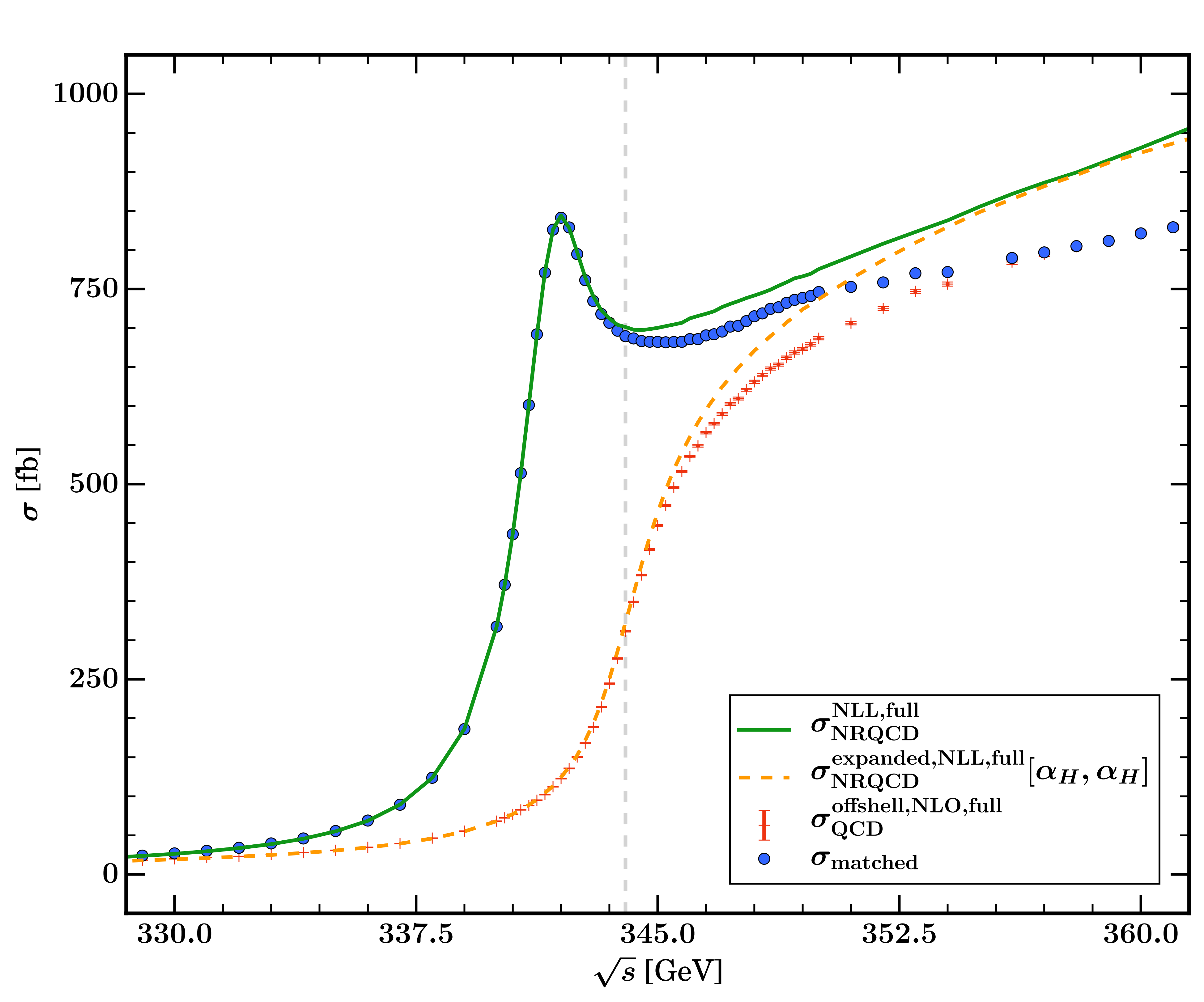
Switch-off function

$$f_s(v) = \begin{cases} 1 & v < v_1 \\ 1 - 2\frac{(v-v_1)^2}{(v_2-v_1)^2} & v_1 < v < \frac{v_1+v_2}{2} \\ 2\frac{(v-v_2)^2}{(v_2-v_1)^2} & \frac{v_1+v_2}{2} < v < v_2 \\ 0 & v > v_2 \end{cases}$$

Threshold-continuum matching



Bach/Chokoufé/Hoang/Kilian/JRR/Stahlhofen/Teubner/Weiss, 2016 & *work in progress*

Conclusions & Outlook

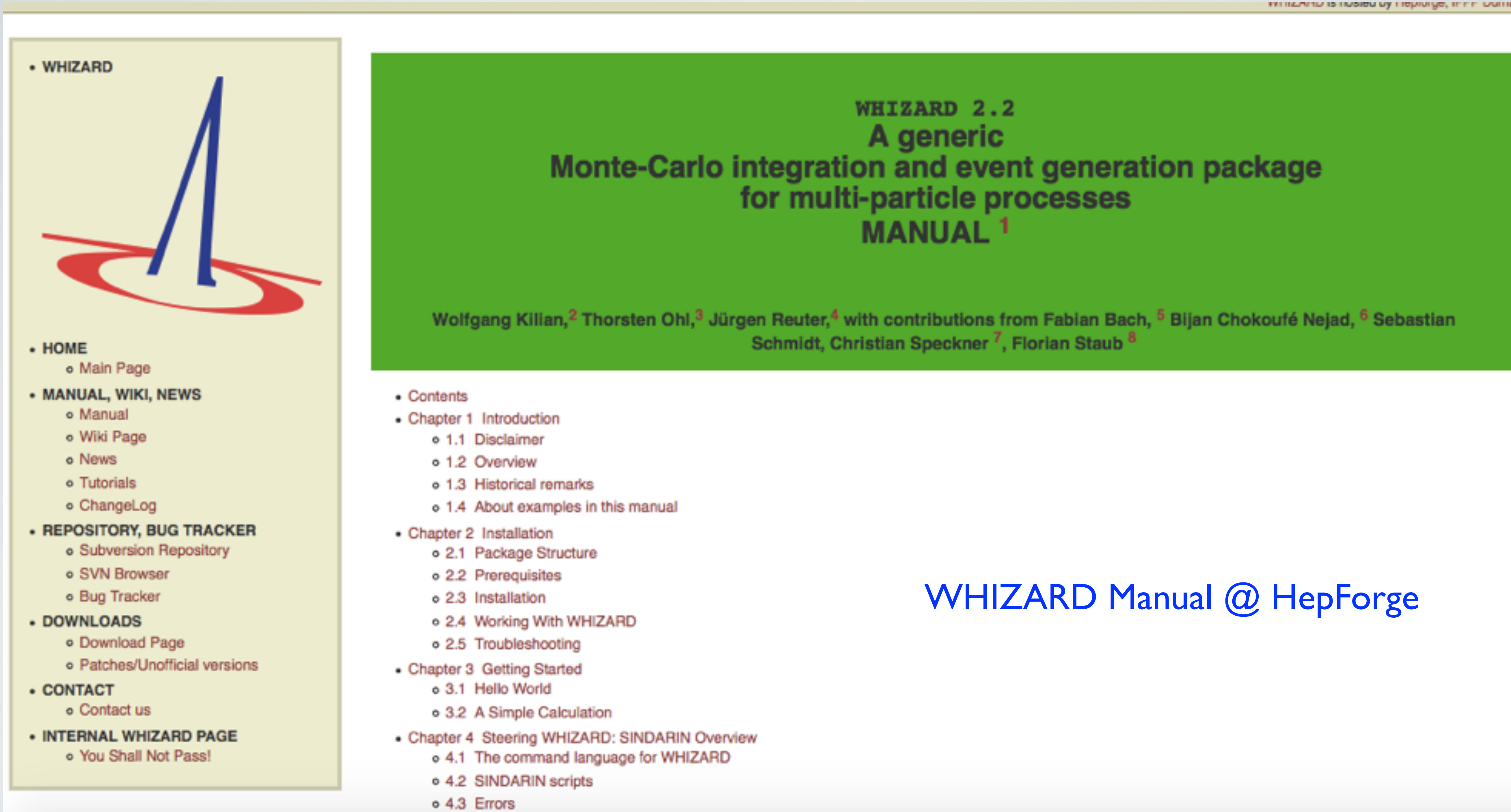
- `WHIZARD 2.3` event generator for collider physics (ee, pp, ep)
- Allows to simulate all possible BSM models
- Allows for all SM backgrounds
- NLO automation: reals and subtraction terms (FKS) [+ virtuals externally] $\to$ `WHIZARD 3.0`
- allows to produce NLO fixed-order histograms
- Automated POWHEG matching (other schemes in progress)
- Top threshold in e+e-: NLL NRQCD threshold / NLO continuum matching
- Virtual Machine for more efficient matrix elements

- Ongoing projects: showers, merging, EW NLO, … , …


New
WHIZARD
QUANTUM
HIGH PERFORMANCE GREASE
Higher Performance
Superior Protection
Learn More

BACKUP SLIDES

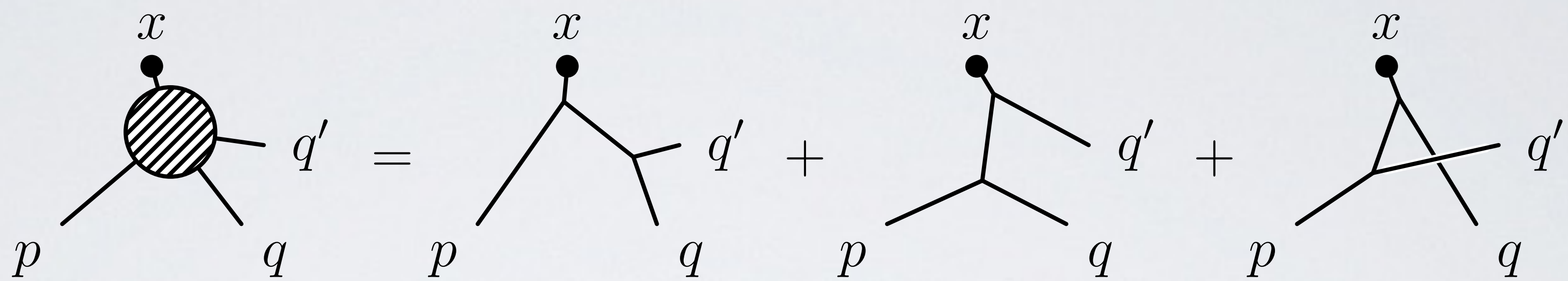
WHIZARD: Manual



WHIZARD Manual @ HepForge

The Optimizing Matrix Element Generator (O'Mega)

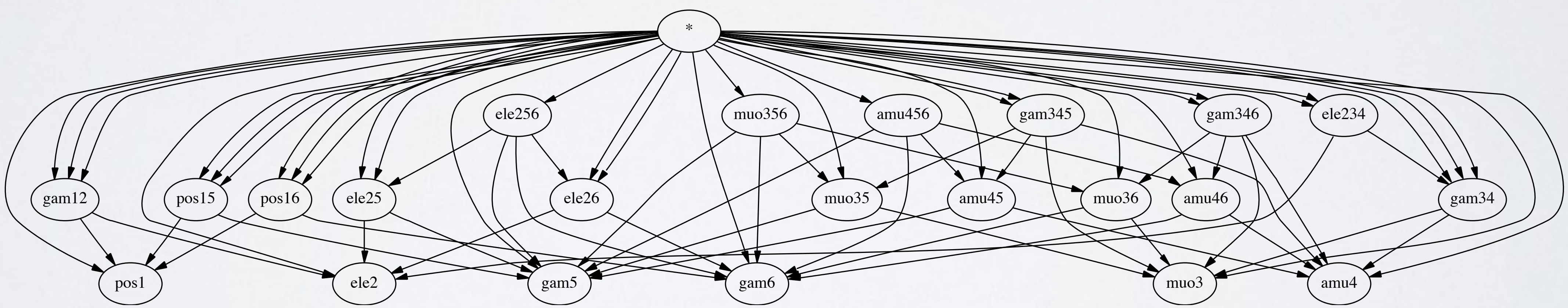
- `O'Mega` [Ohl, 2000; Moretti/Ohl/JRR, 2001; JRR, 2002] computes amplitudes with 1-particle off-shell wave functions (1POWs)



- Possible to construct set of all currents recursively (tree-/1-loop level)

- Keystones K to replace sum over Feynman diagrams

$$\sum_{i=1}^{F(n)} D_i = \sum_{k,l,m=1}^{P(n)} K^{(3)}_{f_k f_l f_m}(p_k, p_l, p_m) W_{f_k}(p_k) W_{f_l}(p_l) W_{f_m}(p_m)$$



- Calculation forms Directed Acyclical Graphs (DAGs), optimized to consist only of the minimal number of connections by `O'Mega`